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Guidelines for Calibration and Application of STORM

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13. ABSTRACT *(Maximum 200 words)*

This report provides specific information on calibration and application of the Storage, Treatment, Overflow Runoff Model (STORM). The STORM model is intended for use in simulation of the quantity and quality of storm water runoff. In particular, the report discusses procedures for collection of rainfall, runoff quantity and quality data. Procedures are recommended for management of the collected data. Recommendations are provided for use of the site-specific data in calibration of the model. The calibrated model can then be used for two important planning components of a storm water study. The first planning component is the prediction of wet-weather pollutographs (mass loading curves) for use in a receiving water assessment model. Therese pollutographs can include both surface runoff and dry weather flow in combined systems. Since the computations are based on land use, the impact of land use change can be evaluated. The second planning component is the preliminary sizing of storage and treatment facilities to satisfy desired criteria for control of storm water runoff. The model will analyze a matrix of combinations of storage and treatment rates. Results include frequency information on quantity and quality of washoff of pollutants and soil erosion, as well as frequency information on quantity and quality of storage overflows.

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Table of Contents

I. INTRODUCTION

This report addresses three main areas of concern to STORM model users. These are:

1. Collection of site-specific data for calibration
2. Model calibration
3. Model application

The recommendations presented here are based on the writer's experience in applications on several studies conducted at the Hydrologic Engineering Center (HEC). The studies were sponsored by several Corps of Engineers District and Division offices.

II. SUMMARY

This report provides specific information on calibration and application of the Storage, Treatment, Overflow Runoff Model (STORM). The STORM model is intended for use in simulation of the quantity and quality of storm water runoff. In particular, the report discusses procedures for collection of rainfall, runoff quantity and quality data. Procedures are recommended for management of the collected data. Recommendations are provided for use of the site-specific data in calibration of the model. The calibrated model can then be used for two important planning components of a storm water study. These are:

1. Prediction of wet-weather pollutographs (mass loading curves) for use in a receiving water assessment model. These pollutographs can include both surface runoff and dry weather flow in

combined systems. Since the computations are based on land use, the impact of land use change can be evaluated.

2. Preliminary sizing of storage and treatment facilities to satisfy desired criteria for control of storm water runoff. The model will analyze a matrix of combinations of storage and treatment rates. Results include frequency information on quantity and quality of washoff of pollutants and soil erosion, as well as frequency information on the quantity and quality of storage overflows.

III. BACKGROUND OF THE STORM MODEL

The quantity portion of STORM was developed for the City of San Francisco by Water Resources Engineers, Inc., (WRE) of Walnut Creek, California. The water quality computations were added in 1973 by WRE while under contract with the HEC. Since then, the HEC has added other capabilities including snowmelt and land surface erosion computations and prespecified hydrographs. Resource Analysis, Inc., of Cambridge, Massachusetts, added the capability to simulate the quantity and quality of dry weather flow. The HEC added the U.S. Soil Conservation Service (SCS) Curve Number Technique for runoff computation and the SCS unit hydrograph technique. A future version will include channel routing and combining, and a "planning level" stream water quality module.

IV. STORM CONCEPTS

1. General. STORM is a continuous simulation model that can be used for prediction of the quantity and quality of storm water and dry weather flow (domestic, commercial, industrial and pipe infiltration). The model provides analyses that can be used to satisfy two primary (but related) study objectives. These are (1) prediction of wet weather pollutographs that can be used in a receiving water assessment model and (2) provide statistical information to aid in the selection of storage capacities and treatment rates required to achieve desired control of storm water runoff.

Wet weather pollutographs can be predicted for individual historical events. The pollutographs consist of hourly rainfall, runoff, masses of pollutants, and pollutant concentrations. This information can be used directly by a receiving water assessment model.

Another portion of the output from STORM provides statistical information based on an analysis of the hourly precipitation record. Statistics, such as average annual runoff, average annual washoff of each pollutant, average annual overflow from storage, and average annual pollutant overflow from storage, are provided. This information can be used to aid the selection of storage capacities and treatment rates required to achieve desired control of storm water runoff.

Runoff quantity can be computed by one of three methods, the coefficient method, the SCS curve number technique or a combination of the two. In the coefficient method, average annual runoff coefficients for the pervious and impervious areas of the watershed are specified, and subsequently, weighted according to the total fraction of impervious area in the watershed so as to obtain a single composite runoff coefficient. This coefficient is then used for each rainfall event in the precipitation record to calculate runoff excess above depression storage regardless of rainfall or soil characteristics. This method may not produce accurate or properly shaped hydrographs for individual rain events, but, when calibrated, may produce sufficiently accurate volumes of runoff.

The SCS Curve Number Technique uses a simple curve to relate accumulated runoff to accumulated rainfall. The curve number is related to the soil type and antecedent moisture conditions. The procedure includes use of an initial abstraction (depression storage) variable which must be exceeded before any runoff can occur for a given storm. Thereafter, the program operates on the curve for determination of runoff. The curve approaches a 45 degree slope, i.e., near zero incremental infiltration would occur at the end of a very large storm. Since STORM is a continuous simulation model, only initial curve numbers (for each land use) are required. The model computes the soil moisture storage capacity at the beginning of each storm in the record based on recovery of soil moisture capacity, initial abstraction and percolation during dry periods. The curve number is expressed in terms of inches of soil moisture storage for input to the model and for computations.

The combination method uses the SCS method on pervious areas and the coefficient method on impervious areas of the watershed.

Storm water quality is computed by using an exponential washoff equation. The equation relates the mass of pollutants washed off during each hour to the current mass of pollutants on the watershed, the runoff rate, and an exponent governing the rate of pollutant washoff.

There are two methods by which the pollutant accumulation may be simulated. In the dust and dirt method, the mass of each pollutant on the watershed is computed as a fraction of the net accumulated dust and dirt on each land use at the beginning of each period of rainfall. The dust and dirt accumulates at a linear rate for each land use during dry hours. Calibration of this method involves adjustment of the dust and dirt accumulation rates, the pollutant fractions of the dust and dirt, and the washoff coefficient so that the predicted pollutant concentrations most nearly match those from measured data. In the daily pollutant buildup method, the mass of each pollutant is computed by a pollutant accumulation rate for each constituent in terms of pounds/acre/day for each land use. The pollutants build up linearly during dry hours. Calibration of this method involves adjustment of the daily pollutant accumulation rates and the washoff exponent.

The overall model operation involves the interaction of 8 main processes. These are: precipitation, runoff, pollutant accumulation, pollutant washoff, dry weather flow, storage, treatment, and overflow. The program computes runoff from rainfall or rainfall plus snowmelt and the associated pollutant washoff. Runoff in excess of the specified treatment rate is diverted into storage for subsequent treatment. Runoff in excess of both the treatment rate and storage capacity is considered overflow and is diverted directly into the receiving waters. The program provides considerable information on the frequency, quantity and quality of overflows. Figure 1 shows a schematic representation of the major processes modeled by STORM.

The reader is referred to the STORM user's manual (Reference 2) for details of the program operation, input data description, and samples of input and output.

2. Limitations. STORM has several limitations associated with the manner in which calculations are made and the nature of certain input variables. The model uses lumped parameter hydrologic techniques for computing precipitation excess and defining subbasin runoff. Empirical techniques are used for computing pollutant washoff and land surface erosion and normally require calibration using site-specific data for the study watershed.

Another limitation is the one hour computation interval. The main reasons that STORM uses a one hour computation interval are that continuous hourly precipitation records are usually available on magnetic tape for most locations and the one hour interval is probably the lower limit in terms of manageability of data for a continuous analysis and computer processing time. The one hour interval affects the lower limit of size of subbasins that may be modeled. One should not expect STORM to produce properly shaped hydrographs for subbasins having times of concentrations less than one hour. In most planning studies, however, the one hour interval should not represent a limitation since the subbasin sizes are normally large enough to have times of concentrations greater than one hour.

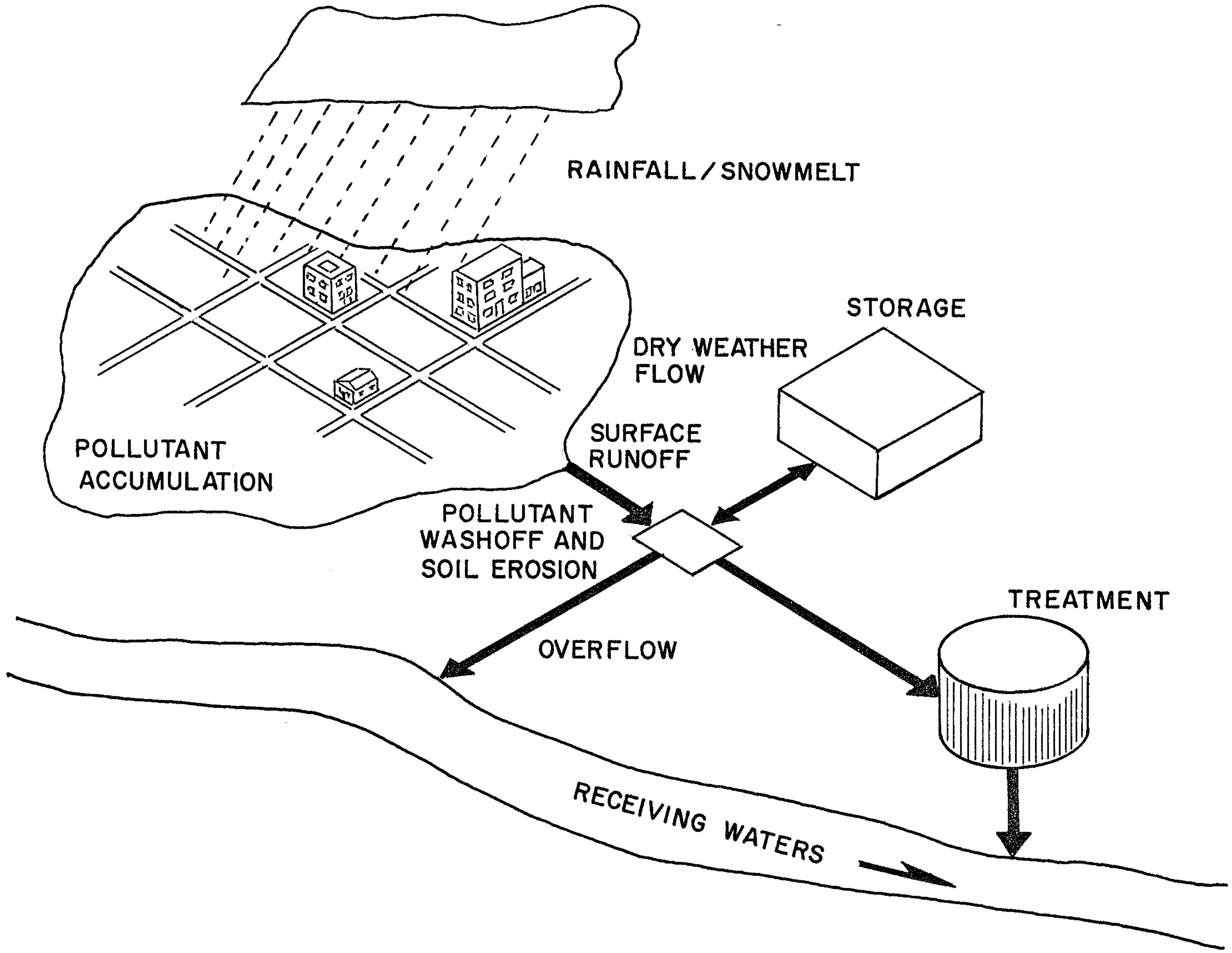


Figure 1. MAJOR PROCESSES MODELLED BY STORM

V. INPUT DATA REQUIREMENTS

1. Summary. The following is a summary of input data required by the major program options. Chapter VI presents detailed information on collection and management of the required data for calibration.

Data	Source
1. Hydrological Data	
Hourly precipitation	U.S. National Weather Service
Evaporation	U.S. National Weather Service
a. Coefficient Method	
Depression Storage	Hydrologists
Runoff coefficient for pervious areas	Analysis of historical rainfall-runoff records
Runoff coefficient for impervious areas	Analysis of historical rainfall-runoff records
b. SCS Method	
Maximum soil moisture retention capacity	Technical literature supplemented by advice from local SCS hydrologists
Maximum initial abstraction capacity	Technical literature supplemented by advice from local SCS hydrologists
Maximum soil infiltration rate	Technical literature supplemented by advice from local SCS hydrologists
Starting soil moisture	Technical literature supplemented by advice from local SCS hydrologists
Starting initial abstraction capacity	Technical literature supplemented by advice from local SCS hydrologists
Unit hydrograph peak rate factor	Technical literature supplemented by advice from local SCS hydrologists
Time of concentration	Technical literature supplemented by advice from local SCS hydrologists

Data	Source
c. Snowmelt (degree-day method)	
Melt temperature threshold	Hydrologists
Starting snowpack water equivalent	Hydrologists
Melt rate coefficient	Hydrologists
Average daily or max and min daily temperature	U.S. National Weather Service
2. Land Use-Related Data	
Area of watershed	Topographic maps
Percent of watershed in each land use	Land use maps
*Percent imperviousness for each land use	Aerial photographs or field surveys
*Street gutter density	City street maps
*Street sweeping interval for each land use	City Department of Public Works
3. Water Quality-Related Data	
a. Surface Pollutant Data	
*Dust and dirt accumulation rate for each land use	Street sweeping program
*Pollutant fractions of the dust and dirt (fractions of suspended solids, settleable solids, BOD, total nitrogen, total orthophosphate and total coliform	Lab analysis of the dust and dirt
Pollutant accumulation rates	Field sampling program
b. Storm Runoff Data	
Concentrations of above pollutants in storm runoff for several storms	Field sampling program

Data	Source
c. Dry Weather Flow	
Population is the minimum data requirement, but several options are available for computing the characteristics of dry weather flow. The options require certain data on quantity and quality of domestic, industrial, commercial, and pipe infiltration flows	City Department of Public Works
4. Soil Erosion (Universal Soil Loss Equation)	
Soil classifications for all soils in the watershed (including slope)	Soil maps
Soil erodibility factors for each soil type	SCS soil scientists
Ratio of maximum hourly rainfall intensity to the maximum 30 minute intensity	Technical literature
Overland flow erosion distance	SCS soil scientists
Ground cover factors	SCS soil scientists
Erosion control factors	SCS soil scientists
Sediment delivery ratios	SCS geologists

* Required only for dust and dirt method of pollutant accumulation

2. <u>Discussion of Data Sources and Input Variables.</u>

a. Hydrologic Data. The main block of data required by STORM is the hourly precipitation record. The model can accomodate an unlimited amount of hourly precipitation data. A separate gage may be used for each subwatershed. Normally, ten to twenty years of data will contain adequate statistical representation of a given subwatershed. Several gages may have to be used in a study of a large area where rainfall patterns are known to have spatial variation. Since an individual gage record represents point rainfall, the rainfall record may have to be corrected so as to represent basin average precipitation. A single coefficient is available in the program for correcting the rain record. If the single correction coefficient is not judged to be adequate, the user can develop his own basin average precipitation record to be input to the model. Precipitation data are available on magnetic tape, from the U.S. National Weather Service (Format No. 488) for stations in the U.S. Otherwise, the hourly data must be punched on cards in the format for STORM.

There will often be situations that existed which caused the rain gage to be inoperative for a few hours to a few days. This condition is "flagged" by a special character on the tape in the hours that it occurred. In addition, a value will be found at the end of the sequence of "flagged" hours that represents the total precipitation that occurred during the gage failure. These situations must be corrected. Not only would it be incorrect to allow a large amount of precipitation to remain in one hour, but also the special characters would not be accepted by the program format under which the rainfall data is read. The rain data must also be placed in the format described in the users manual. The HEC has developed a preprocessor program which will read the original tape, correct the gage failures by distributing the precipitation evenly among the hours, reformat the data, and place the data in a disc-storage location. This allows it to be called up quickly without having to go back to the original tape.

Depression storage (initial abstraction) is expressed in terms of inches of water depth over the entire watershed for the coefficient method (each land use for the SCS method). It is assumed to represent the sum of the amount of storage available in small depressions in the land surface, the amount intercepted by vegetative cover, and the amount of infiltration that occurs during the time when depression storage is being filled.

The runoff coefficients in the coefficient method are very important parameters since they govern the quantity of runoff (and the quantity governs the quality of runoff). The values should represent average yearly fractions of rainfall (in excess of depression storage) that runs off the watershed. In the coefficient method, the impervious area runoff rate is used to "drive" the pollutant washoff equations.

The variables required for the SCS runoff method are used for continuous soil moisture accounting. All are important since they govern the manner in which precipitation losses are computed. Assistance in selection of the magnitude of these variables for a given watershed can be found in References 3 and 4. The most important variables (SMAX, DEPR, RATEIN, and PERCMX) can normally be obtained from SCS soil survey reports.

The snowmelt option requires four easily obtainable variables: air temperature, melt temperature, melt rate coefficient and starting snow pack water equivalent. The program compares each day's average temperature with the temperature threshold in order to decide whether precipitation falling on that day is rain or snow. If it is snow, it goes into the pack where it remains until a day occurs having a mean temperature above the threshold. Melt is then computed by applying the melt rate coefficient to the difference between the mean temperature and the threshold temperature.

b. Land Use-Related Data. The land use-related data make up the second main category of input. The land use data are usually available from local planning agencies. In the San Francisco study (Reference 5), a computerized system was implemented whereby the land use for each subbasin in the study is produced by a program which searches a magnetic tape of digitized land use information gathered by a satellite (LANDSAT). This technique should greatly simplify the process of obtaining existing land use for a storm water runoff study.

The percentage impervious area is an important variable in the coefficient method of computing runoff. A distinction is to be made between gross impervious area and connected impervious area. The latter is the variable that should be used in the model since it is most highly correlated with immediate runoff quantity and quality. An example of connected impervious areas would be direct connection of a rooftop, driveway and gutter to a storm sewer pipe system. Impervious areas which drain onto pervious areas should not be included in this variable. Instead, the runoff coefficient for the pervious areas should be increased to account for the additional runoff due to non-connected impervious area. If gross impervious area is available from techniques which use remotely sensed information, it would be desirable to develop a correlation between connected and gross impervious area by field studies.

c. Water Quality-Related Data. The surface pollutant data required are dependent on the option chosen for pollutant accumulation. The first option (IPACUM=1) is intended for use in an urbanized watershed where the majority of pollutants can be assumed to come from street accumulation of dust and dirt. This option requires a dust and dirt accumulation rate for each land use, as well as pollutant fractions of the dust and dirt. The second option (IPACUM=2) requires only a pollutant accumulation rate for each land use. It is intended to be used in areas where a significant portion of the pollutant discharge comes from sources other than streets. An example would be a basin composed of both urban and nonurban land uses or a totally nonurban basin. This option could also be used on an entirely urban area since the dust and dirt accumulation rate and pollutant fractions can be converted to pollutant accumulation rates.

The second option for surface pollutant accumulation does not require the collection of street contaminant data. This option relies entirely on using storm runoff data to compute annual pollutant discharges which are used to obtain short term accumulation rates. The advantages of this option are that it does not require street contaminant data and it can be used where the street surfaces are not believed to be the major contributor of pollutants. Its disadvantage is that a larger amount of storm runoff data must be collected.

Storm runoff data are important for calibration of the model. The data are required to estimate the pollutograph for individual runoff events, as well as the annual discharge of a given pollutant. This topic will be covered in detail in Chapter VI.

Four options are available for computing the quantity and quality of dry weather flow. The options range from simply specifying the total population for the watershed to inputting the hourly variation of the quantity (as well as quality) of the dry weather flow.

d. Soil Erosion Data. Input data for the land surface erosion comes from several sources. The soil type is normally available from soil maps. The program will allow use of a representative sample of watershed area to avoid repetitious manual coding of soil type information. The ratio of 30 minute to hourly rainfall intensity is available from technical literature or the National Weather Service. The other variables for this option are rather specialized in nature. Therefore, the local Soil Conservation Service office should be consulted to provide assistance in selecting the magnitude of these variables as well as assistance in interpretation of results from the soil erosion analysis.

The land surface erosion option is to be used only for sediment production studies. Sediment loads calculated by this option are not added to the suspended or settleable solids loads and therefore are not reflected in the pollutograph, event or annual values of suspended and settleable solids. In studies where soil erosion may be a contributor, but not necessarily the major source, the loading coefficients for suspended and settleable solids must be adjusted in order for the soil erosion to be reflected in the quality output.

VI. COLLECTION AND MANAGEMENT OF FIELD DATA REQUIRED FOR CALIBRATION

1. Pollutant Data. The two types of data required are average annual dust and dirt accumulation rates and the pollutant composition of the dust and dirt. Data should be taken from representative portions of each land use. A representative length (perhaps 100 feet) of guttered street should be selected for study in each land use. Criteria to judge its representativeness could include average traffic volume, average population (or housing) density, average age of structures, or others considered to be relevant. The measurements should be made during a dry season. A dry day accumulation interval should be selected (perhaps 2 weeks). The entire length (and width) of the 100 foot section of street should be "swept". A vacuum device, such as that used by shopping centers to clean parking lots, may be used. Brooming or washing may have to be employed to insure that all fine material is removed.

The first sweeping at each site cannot be used to calculate accumulation rates since the accumulation time is unknown, although it can be analyzed for pollutant fractions. Significant runoff cannot be tolerated during the accumulation intervals. The field team will have to be alert to the possibility that runoff could occur during any accumulation interval and thus invalidate the results for that particular interval. The procedure must then start anew, discarding the first sweeping and then sweeping again at the end of the accumulation period.

The material collected after each accumulation period should be screened over a 1/4 inch mesh screen. The material passing the screen should be weighed. A sample of the material should be sent to a laboratory for analysis of moisture content, fractions of suspended solids, settleable solids, BOD, total nitrogen, total orthophosphate or other pollutants. At least 6 sweepings should be accomplished during the dry season. The field operations should be coordinated with city officials so as to obtain approval and/or assistance, such as providing traffic barricades for use during sweeping. The above data are required for IPACUM=1.

2. Storm Runoff Data. The purpose of this section is to outline a procedure for collecting storm runoff data to calibrate STORM on a given area. The basic premise is to collect sufficient data to adequately define the pollutographs for the required pollutants for enough storms to estimate the annual pollutant discharge. Figure 2 shows concentrations of two pollutants measured during a storm runoff event. Figure 3 shows a pollutograph for BOD for a single event.

In order to obtain a better definition of the quality of runoff, small portions of the study area should be selected for detailed analysis. In this approach, a test watershed is chosen to represent each of the major land uses in the study area. The model can then be calibrated for each land use, thereby evaluating those coefficients which are a function of land use. A major assumption of this approach is that results from a test watershed will be transferrable to other areas of the same land use. The use of test watersheds made up of more than one land use is not recommended because one must make adjustments to the coefficients without the benefit of knowing how they vary with land use.

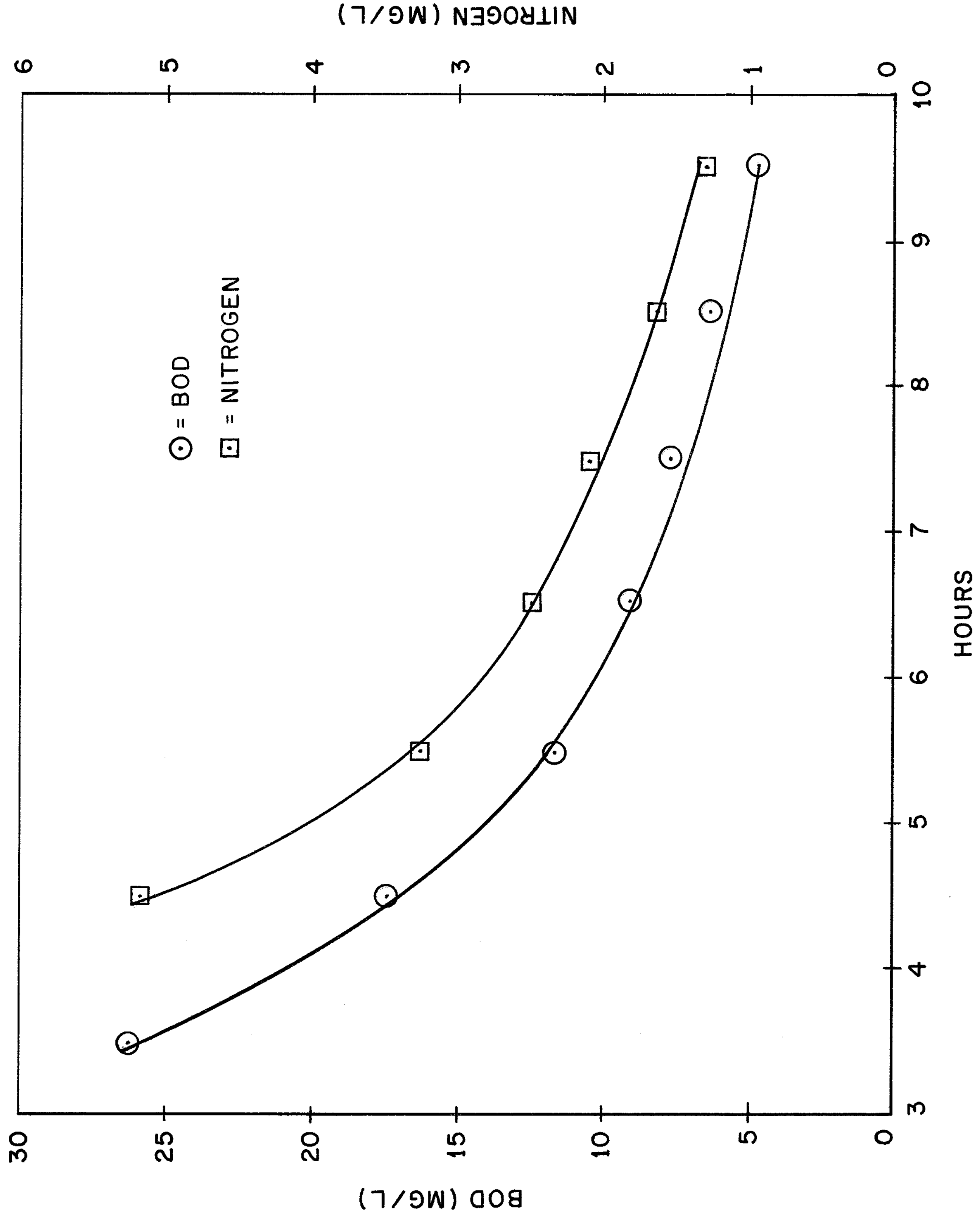


Figure 2

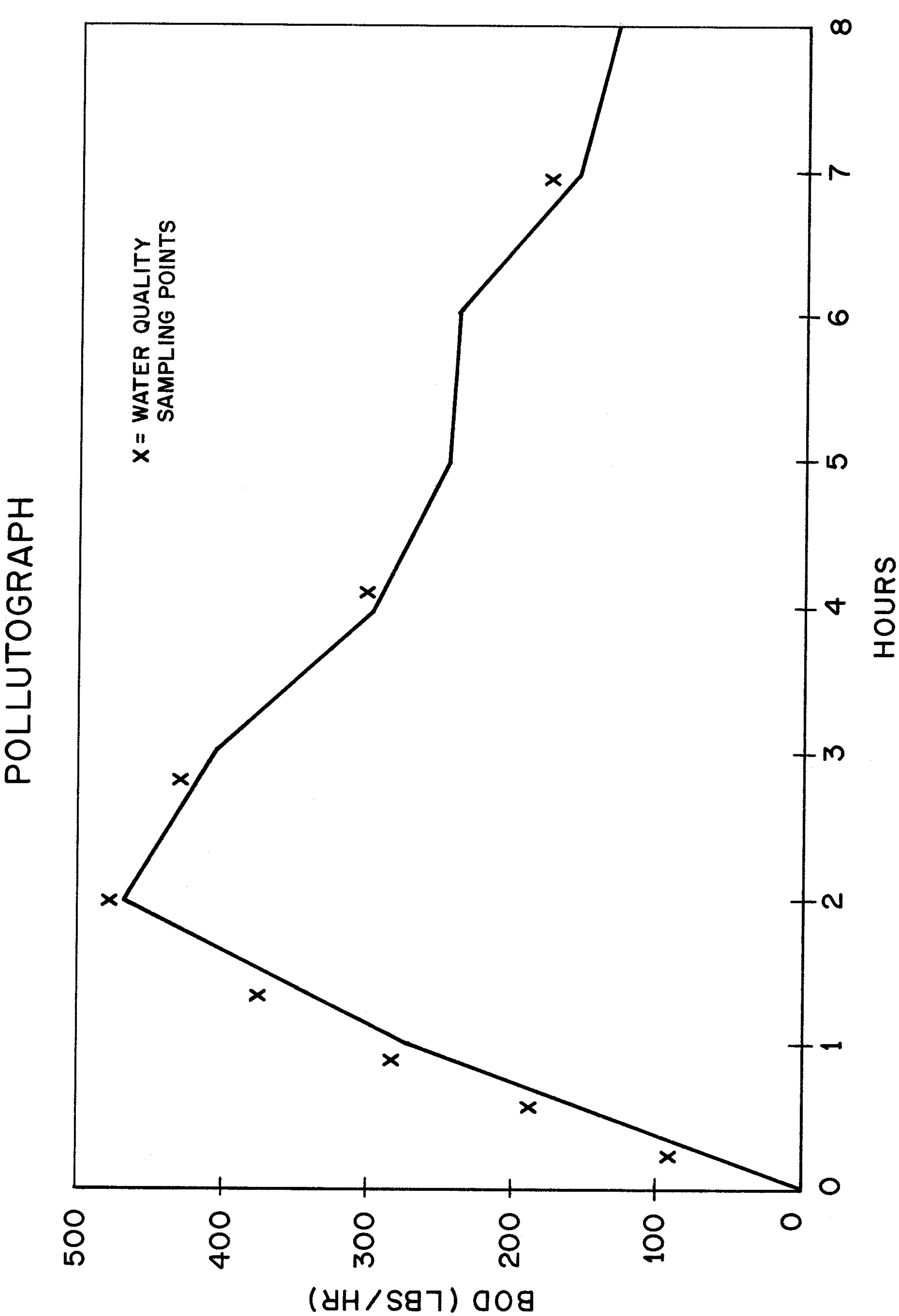

POLLUTOGRAPH
X = WATER QUALITY SAMPLING POINTS
HOURS
BOD (LBS/HR)
0
1
2
3
4
5
6
7
8
0
100
200
300
400
500

Figure 3

Test watersheds must be chosen with good judgement. It is important to choose basins that are small enough to be reasonably homogeneous in terms of hydrologic, pollutant and land use factors, and yet not so small that their response will be too short to allow collection of adequate data. Depending on the time of concentration, basin sizes of 5-10 square miles should be adequate.

Basin average rainfall data are required to operate STORM. A rainfall recorder installed within the basin is most desirable. More than one gage may be required to measure the spatial variation of rainfall across the basin. If more than one gage is used, the data from each applicable gage can be used to compute basin average precipitation (by methods such as the isohyetal or Thiessen) since STORM accepts data from only one rain gage per subbasin. The recorder should be capable of recording as low as 10 minute amounts of precipitation to allow short interval analysis of selected events. It would be desirable to have several years of hourly rainfall data. The rain gage should be installed according to procedures in Reference 6.

Runoff quantity data are required to calibrate the runoff prediction in the model. Water quality predictions also depend on adequate representation of the runoff process. A streamflow stage recorder must be installed at the outlet of each test watershed. Normally, the nearest U.S. Geological Survey office can be employed to install and operate the gaging stations. A reliable relationship between flow rate and stage should be developed prior to the study. Rating the gage may take several months depending on the runoff characteristics of the test watersheds.

If the U.S. Geological Survey cannot install and operate the gaging stations, it should be accomplished according to procedures outlined in Reference 7.

Adequate storm water quality data are the most difficult and costly to obtain. Ideally, all significant runoff events during one or more years should be measured so as to obtain estimates of the average annual discharge of selected constituents. Sampling costs usually govern the number of storms that can be measured, therefore the researcher must be satisfied with measurements from a small number of storms. In this case, it may be possible to develop a relationship between pollutant discharge and runoff intensity, number of dry days prior to the event, or other relevant variables. This procedure can then be used to estimate the average annual loading of a given pollutant. In the San Francisco study (Reference 5), it was not possible to choose which storms were to be monitored, a priori. Due to the extremely erratic nature of runoff occurrences in that area, the researchers had to attempt to measure each runoff event in hopes that it would be significant.

Sampling techniques range from completely manual to completely automatic. Each technique has met with limited success depending on the procedure, equipment and rainfall-runoff characteristics of the test watersheds. In the manual approach, the field team must rely upon weather forecasts to prepare for sampling an event. At the onset of precipitation, the team must be immediately dispatched to the sampling site. Sampling must begin immediately so as to obtain measurements that represent the "first flush" or initial washoff phenomenon. Sampling must continue at frequent intervals (say 15 minutes) until the peak is reached since the majority of the mass of pollutants are assumed to be washed off during this period. When the hydrograph peak is reached (this may be difficult to recognize since many storms produce multi-peaked hydrographs) the sampling frequency can be reduced (to say, 1 hour).

The opposite extreme is using a fully automated approach. Equipment is available to pump many samples from the stream into separate sample bottles at specified intervals, usually 5-60 minutes. Some devices, such as that used by Florida Institute of Technology, (Reference 8) can refrigerate the samples for up to 48 hours to preserve the samples before they are retrieved by the field crew. These devices can be programmed to begin sampling at a significant rise in stage, and some will sample at preset increments of either time or stage. Most automatic sampling equipment that has been used is of the type that commences and samples automatically, but relies upon a field crew to retrieve the samples within 1-2 hours.

The automatic sampling technique has had varied success in storm water applications. The equipment seems to be prone to mechanical failure. Runoff is intermittent requiring that the equipment lie idle for some time and yet function properly at the beginning of a runoff event. The situation is compounded by the nature of storm water. The flow rate is extremely variable, and the water is often laden with debris which causes clogging of suction lines or pumps. In the San Francisco Study (Reference 5), automatic sampling at the Castro Valley watershed was discontinued in 1973 because of mechanical failure and clogging. Since then, the field team has relied upon reaching the sampling site within 30 minutes after runoff begins. Part of the initial runoff was sacrificed in order to insure that samples were collected throughout the runoff event. However, in the Strong Ranch watershed, the automatic equipment was retained since the site is within walking distance of the field office, and a technician was able to insure that the equipment would begin sampling at the correct time and continue sampling throughout the event.

Sampling must be accomplished so as to provide enough data points to adequately define the pollutographs for each selected constituent. The pollutographs are integrated to determine the total discharge of pollutants by each measured event. Sampling frequency and total duration of sampling are important factors in defining the pollutographs. A rule of thumb is that 4-6 points should be defined on the rising limb of the hydrograph and 2-4 on the descending limb. If 6 points on the rising limb are chosen, the sampling frequency should be approximately 1/6 the average time to peak for the basin. When using automatic equipment, more samples than this can easily be collected. Figure 3 shows a good distribution of sampling points throughout a pollutograph.

Regardless of the sampling method, the samples must be handled properly. The sample bottles should be placed in a mixture of ice and water as soon as possible after collection. This is particularly important for samples that will be analyzed for biological parameters such as BOD. These samples should be analyzed within 24 hours. Most physical and chemical constituents can be analyzed later. Laboratory analysis should be performed according to Standard Methods for Examination of Wastewater (Reference 9).

Since the present version of STORM predicts 6 parameters (suspended solids, settleable solids, 5-day BOD, total nitrogen, total orthophosphate, and total coliform bacteria) it is imperative that tests be made for these. Certain other parameters such as pH, alkalinity, dissolved oxygen and total dissolved solids should also be measured regularly. Other parameters such as heavy metals, COD, oil and grease, fecal coliforms, herbicides and pesticides can also be measured if time and funds permit. It may be possible to predict these additional parameters by adjusting the coefficients and equations in STORM used for the other constituents. If the parameters cannot be related to the dust and dirt, sufficient data must be collected to establish a functional relationship between the washoff of that pollutant and measurable parameters such as runoff intensity, number of dry days between events, traffic volume or other independent variables. The maximum number of pollutants predicted during any run cannot exceed 6.

Efficient data handling can greatly simplify a storm water study. Since data are to be taken from 3 main sources, (rainfall, runoff quantity and runoff quality) it is imperative that data coordination be handled by a single informed entity. For example, pollutant concentrations are not very meaningful in themselves, but must be viewed together with flow rate and time. Data can most efficiently be analyzed by placing them on cards so that analysis and plotting of data and results can be handled by computer. The HEC has developed a format for these cards which include precipitation, flow, and concentration data. The format is shown in Figure 4. An example of output from a pollutograph computation and plotting routine developed by HEC is shown in Figure 5.

WATER QUALITY DATA CARD FORMAT

PRECIPITATION-RUNOFF HYDROGRAPH (Q)

- Station Number
- Code*
- Name**
- Year
- Month
- Day
- Continue
- Starting Time
- Time Interval
- Prec (1) /or/ Q (1)
- Prec (2) /or/ Q (2)
- Prec (3) /or/ Q (3)
- Prec (N) /or/ Q (N)

* If the interval is even (as for Prec * Q), insert a "1", otherwise, leave the column blank.

** All names are left justified.

W.Q. PARAMETER CONTROL CARD

- W.Q. Parameter "A"
- Number of W.Q. Parameter "A" Plotting Points
- Plotting Scale Factor*
- W.Q. Parameter "B"
- Number of W.Q. Parameter "B" Plotting Points
- Plotting Scale Factor*

Set up for W.Q. Parameters C,D, and E same as for Parameter A

*Scale Factor	Max Sample Value	*Scale Factor	Max Sample Value
1	10	8	50,000
2	20	9	100,000
3	50	10	1.0
4	250	11	0.5
5	500	12	0.01
6	1000	13	0.001
7	2000	14	0.0001

INITIAL CONTROL CARD FOR PLOT

- Number of hours on X-Axis
- Starting Time on X-Axis
- Number of W.Q. Parameters to be Plotted*

* Maximum number of plots is "5"

Figure 4

W.Q. PARAMETER CARD

Station Number

Code*

W.Q. Parameter Name**

Year

Month

Day

Continue

Time of Sample

Magnitude of Sample (MG/L)

Time of Sample

Magnitude of Sample (MG/L)

Time of Sample

Magnitude of Sample (MG/L)

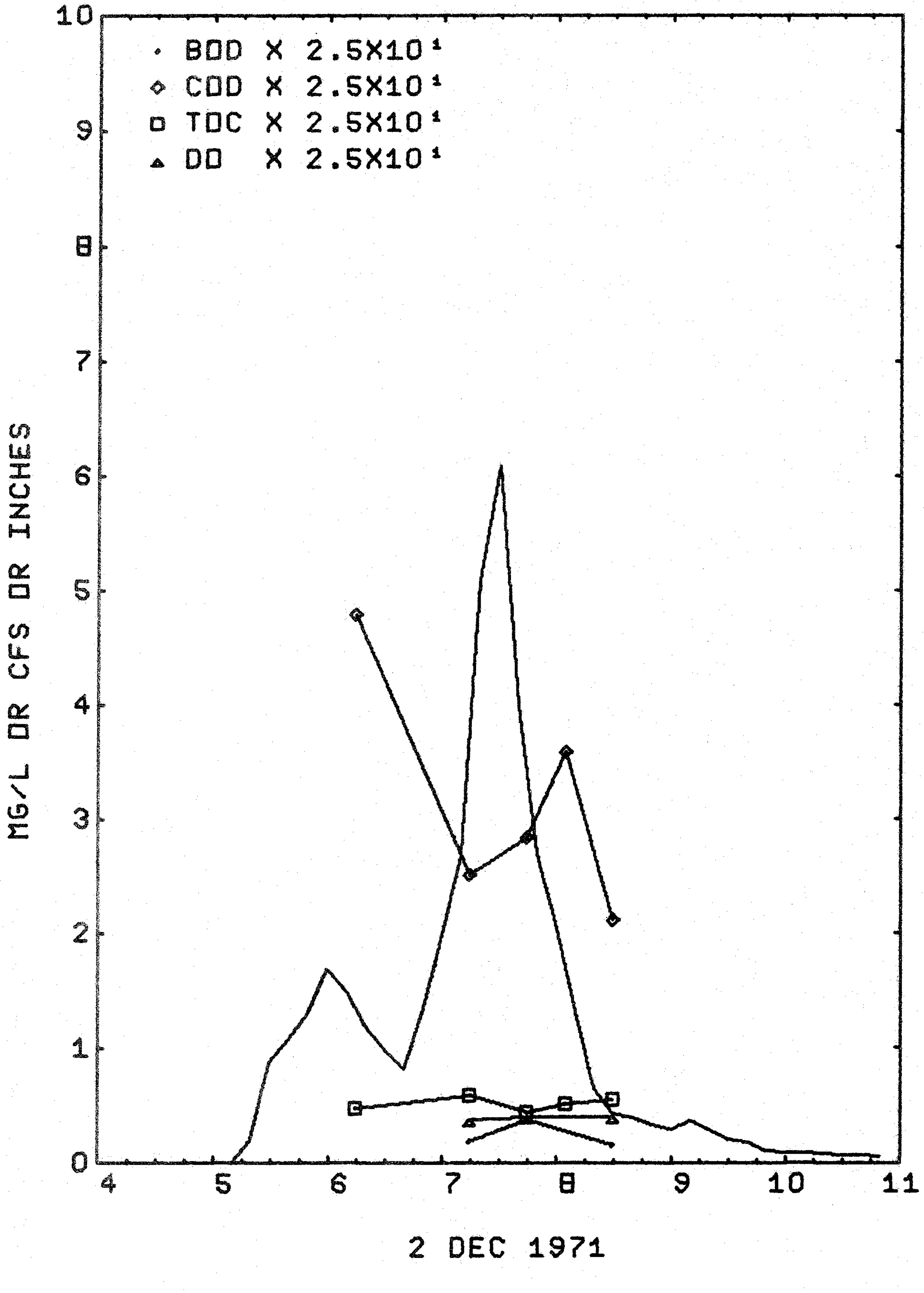
Time of Sample

Magnitude of Sample (MG/L)

* If the interval is even (as for Prec & Q), insert a "1", otherwise, leave the column blank.

** All W.Q. parameter names are left justified.

Figure 4 (con't)



CASTRO VALLEY CREEK

Figure 5

The data can also be submitted to the Environmental Protection Agency for placing in their STORET system for storage and retrieval of water quality data. This makes the data available to anyone in the U.S. who has access to the system. Certain plotting and statistical analysis capabilities are available during an interrogation of the system. The procedures for accessing the STORET system are outlined in Reference 10. An example of data from a STORET retrieval is shown in Table 1.

VII. MODEL CALIBRATION

1. Introduction. Calibration can be characterized as a "mini application". Since the model must be applied to the calibration watersheds, all those variables required for a normal application must be assembled for use in calibration. The procedure entails assemblage of observed data (rainfall, runoff and quality) and land use data followed by successive applications of the model to the test watersheds until the model is satisfactorily calibrated for the study area.

2. Quantity. Model calibration cannot commence until certain data are prepared for input to the model and observed data organized so as to compare with computed results.

Precipitation data must be extracted from recorder charts. These charts usually contain traces which represent accumulated precipitation. The value at the end of each hour can be tabulated. The incremental amounts are found by subtracting the preceding value from each hour's accumulated total. The hourly precipitation must then be coded in the format described in the users manual (Reference 2).

PROCESS DATE 06/11/75
DISTRICT CODE 06

11181008 - CASTRO VALLEY CREEK AT HAYWARD, CALIF.

WATER QUALITY DATA, WATER YEAR OCTOBER 1974 TO SEPTEMBER 1975

DATE	TIME	TEMPERATURE (DEG C) (00010)	SURFACE AREA (SQUARE MILES) (00049)	INSTANTANEOUS DISCHARGE (CFS) (00061)	SPECIFIC CONDUCTANCE (MICROMHOS) (00095)	BIOCHEMICAL OXYGEN DEMAND 5 DAY (MG/L) (00310)	CHEMICAL OXYGEN DEMAND (HIGH LEVEL) (MG/L) (00340)	PH (UNITS) (00400)	ALKALINITY AS CACO3 (MG/L) (00410)
OCT.									
01...	2200	19.5	5.5	.27	1130	--	--	8.1	264
07...	1600	16.0	5.5	.17	992	1.1	26	8.3	274
27...	1925	17.5	5.5	40	232	90	340	--	--
27...	2010	17.0	5.5	32	254	41	270	7.3	34
27...	2030	17.0	5.5	53	236	34	230	7.4	34
27...	2135	16.5	5.5	18	345	48	300	7.5	58
27...	2145	17.0	5.5	126	270	50	410	7.4	47
27...	2250	16.0	5.5	41	218	29	220	7.7	41
27...	2300	16.0	5.5	56	218	24	200	7.4	34
27...	2350	16.0	5.5	21	212	26	170	7.4	37
28...	0005	16.0	5.5	32	248	--	190	7.5	41
28...	0008	16.0	5.5	73	260	32	320	7.4	45
28...	0014	16.5	5.5	100	208	--	810	7.4	38
28...	0018	16.0	5.5	134	160	72	550	7.5	30
28...	0023	16.0	5.5	186	157	64	380	7.5	30
28...	0028	16.0	5.5	178	165	67	500	7.5	33
28...	0052	16.0	5.5	77	127	--	120	7.8	27
28...	0130	15.0	5.5	33	130	19	130	7.6	25
28...	0200	15.0	5.5	20	151	19	230	7.5	30
28...	0215	15.0	5.5	58	223	--	160	7.5	38
28...	0220	15.5	5.5	64	165	18	150	7.5	33
28...	0330	15.0	5.5	35	174	15	100	7.3	31
28...	1135	14.5	5.5	3.8	340	13	84	7.8	77
28...	1835	14.5	5.5	3.6	536	13	100	7.7	220
30...	2210	10.0	5.5	10	1400	--	--	7.9	290
30...	2220	10.0	5.5	9.6	1270	--	--	8.0	280
30...	2255	11.0	5.5	26	425	--	--	7.5	80
NOV.									
07...	1110	14.0	5.5	236	165	84	510	7.7	36
07...	1115	14.0	5.5	286	114	78	500	6.6	17
07...	1120	14.0	5.5	389	86	70	410	6.8	18
07...	1125	14.0	5.5	430	67	55	340	7.5	19
07...	1130	14.0	5.5	441	65	48	290	7.7	17
07...	1135	13.5	5.5	370	64	35	250	7.4	16
07...	1150	13.0	5.5	163	156	29	210	7.5	36
07...	1245	14.0	5.5	27	163	19	100	7.2	33
07...	1305	14.0	5.5	84	151	48	120	7.2	30
07...	1320	14.0	5.5	196	104	29	110	7.2	23
07...	1330	14.0	5.5	208	76	19	140	7.0	17
07...	1410	14.0	5.5	56	102	13	62	7.1	20

Table 1

STORET Data

The next step is assembling the runoff quantity data. If the U.S. Geological Survey handles the streamflow gaging, the data will normally be furnished in the form of mean daily discharges plus selected individual storm hydrographs. Monthly and annual runoff amounts are also furnished. Because processing and publishing the flow of data often takes several months, sufficient time must be allowed for this item. If the stream gaging is handled "in-house", the stage recorder charts must be converted to flow rates by use of the rating curve (previously established) for each individual gaging station. The hydrographs are then integrated so as to produce statistics such as individual hydrograph runoff volumes, monthly runoff volumes, and annual volumes.

The quantity calibration involves adjustment of certain coefficients which regulate the volume and timing of runoff. In the coefficient method, the first factor to adjust is the runoff coefficient for the pervious areas of the watershed (CPERV) so that the observed and computed magnitudes of total period runoff volume, annual volume and monthly volume show fair agreement. Since the coefficient method is a very crude model of the urban runoff process, it may not be meaningful to compare individual event volumes. Other variables that can be adjusted, although to a lesser extent, are the runoff coefficient for the impervious areas (CIMP) and the initial abstraction (DEPRS).

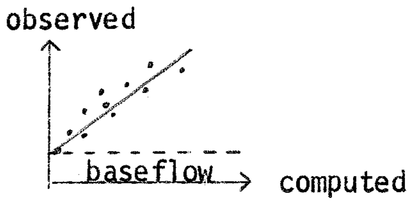
The SCS runoff method should produce more accurate magnitudes of runoff excesses. Therefore, when using this method, one should not only produce more accurate total period, annual, and monthly volumes of runoff, but also more accurate individual hydrograph volumes.

The unit hydrograph procedure should increase the accuracy of the timing and shape of the individual hydrographs. Table 2 shows the result of preliminary sensitivity tests using the SCS methods.

3. Quality. Runoff quality data must also be assembled. A tabular listing should be made of the date, time and concentrations in mg/l for the 6 parameters predicted by STORM (coliforms in 1000 MPN/l). Table 1 shows such a listing. Pollutographs for each parameter should be computed by multiplying the concentrations by the water discharge rate at the time of measurement. The values should be converted to lbs/hr. The pollutographs should be integrated so as to obtain the total pollutant discharge for each runoff event.

Results from the street sweeping program must be expressed in appropriate units for input to the model. The dust and dirt collected at the end of each accumulation interval should be divided by the interval, averaged, and expressed on a dry weight basis for each land use (lbs/100 ft. gutter/day). The constituents of the dust and dirt should be expressed in terms of average pounds of pollutant per 100 pounds of dust and dirt for each land use. This will provide the data for use of pollutant accumulation method number 1 (IPACUM=1).

If street sweeping data are not available or if the streets are not believed to be the major source of pollutants, the second method for pollutant accumulation must be used (IPACUM=2). This method relies upon the stormwater runoff data alone to establish the accumulation rate for each pollutant. Several assumptions must be made in order to express the pollutant accumulation rates in terms of pounds/acre/day. The first, and



L = little effect, M = moderate effect,
H = high effect

I = increases runoff, or slope of line
D = decreases runoff or slope of line

N/C = no significant change

Increase These Variables		Effects on: Low flows	High flows	Slope	Y intercept
Coefficient Method	CPERV	MI	MI	N/C	D
	CIMP	MI	MI	N/C	D
	DEPRS	MD	MD	N/C	I
SCS Method	EERC	LI	MI	D	2/
	EPRC	LI	MI	D	2/
	DEPR	LD	MD	I	2/
	ACTIA	MD 1/	HD 1/	I	2/
	SACT	LD 1/	LD 1/	D	I
	SMAX	MD	MD	I	I
	RATEIN	LD	LD	N/C	I
	PERCMX	LD	HD	I	2/
	RECVRT	LD	MD	I	2/
	Method 2 to Method 3	HE	MI	D	2/

1/ Only affects first months

2/ Depends on whether slope rotation changes as fast as translation

Table 2

STORM Sensitivity Tests (runoff quantity) probably the most significant, is that the annual mass discharge of a given pollutant can be estimated by measurement of the mass discharges for several selected events and extrapolation to an entire year. The extrapolated can be done by correlation with relevant washoff variables such as water runoff volume and rates. The second assumption is that the daily accumulation rate can be estimated by dividing the total annual mass discharge by the average number of dry days per year.

It is recognized that the accumulation rates must vary seasonably. However, no data are available to quantify this variability. Therefore, one must proceed with a single linear daily accumulation rate. A third assumption is that the net change in annual mass discharge of pollutants is negligible.

The state-of-the-art in urban storm water quality modeling precludes highly accurate simulation of pollutographs. However, the quality aspects of STORM must be calibrated so as to produce results as accurate as possible. It may not be possible to reproduce the time value of concentrations in which case the emphasis should be placed on reproducing the mean concentration and the total mass of pollutants washed off by the observed events.

Quality calibration can commence only after an adequate quantity calibration has been completed. An initial trial can be made using the suggested values for pollutant accumulation (lbs/100 ft gutter/day or lbs/acre/day). The event numbers to be studied in detail can be taken from this initial run and a preliminary inspection of the extent of agreement between observed and computed data can be made. Comparisons should be made first with observed and computed pollutant concentrations (displayed in the pollutograph analysis for the selected observed events).

The primary coefficients to be adjusted are the pollutant accumulation rates and the washoff exponent, the latter being a coefficient which governs the rate of washoff of each pollutant. In the dust and dirt method, the dust and dirt accumulation rate for each land use can be adjusted first depending on whether all pollutant concentrations are too low or too high. Once the concentrations are nearly correct, the pollutant factors of the dust and dirt can be adjusted. (Ideally, the model should be calibrated on single land use basins, as recommended earlier.) The washoff exponent can also be adjusted if the data show a different change in concentration with time during each event. (A higher exponent will produce a higher rate of washoff.) In the daily pollutant accumulation method, the accumulation rates for each pollutant and the washoff exponent are adjusted until fair agreement exists between the measured and computed data. After agreement in concentrations is accomplished, one should compare the total mass of each pollutant washed off with the computed values for the selected events.

VIII. MODEL APPLICATION

1. General. This section presumes that STORM has been properly calibrated on the test watersheds (both quantity and quality). The remaining tasks involve application to the entire study area.

The first step in an application is to delineate the entire study area on a map. A good scale to use is the 1:24,000 size of the U.S. Geological Survey. The study should be outlined by drainage areas. The study area must be subdivided (by drainage, again) for application of the model. The subdivision is required to generate loadings at correct locations along the receiving stream, and for routing flows. A usable number of subbasins is 25-30 since a data deck must be prepared to each subbasin. Since the program has the capability to do several subbasins in one run, it is recommended that the receiving stream be subdivided into a number of subreaches, say, 4-5. The loading points for each reach can be run at the same time. If computational or storage capability is not available to run several subbasins at a time, they may be individually run. In either case the STORM output is stored on tape/disk for later input to a receiving water assessment model.

If rainfall gage locations other than those used in the calibration phase are to be used, that data must be assembled for use in the application. The rain data can usually be obtained on magnetic tape from the National Weather Service in Asheville, North Carolina. Some editing of the data supplied on tape may be required, as discussed in Chapter V. Once the point rainfall data have been satisfactorily edited, reformatted, and placed in a usable storage location, a decision must be made in regard to which gages to associate with the various subbasins. The proximity of the centroid of the basin to the rain station is probably the major consideration. A decision must also be made as to whether to use the point rainfall or to estimate subbasin average precipitation. STORM has the capability of multiplying each hour's precipitation amount by a constant (specified by the user) for use in situations where this is deemed adequate.

The next major block of required input data is the land use information. Land uses are specified in terms of the percentage of each in the subbasin. In the Oconee River Study (Reference 11), the land use percentages were calculated from a computer-stored data file of basin land use delineated on a 1.5 acre grid cell basis. STORM was modified to retrieve this information directly from tape/disk. This avoided the expense of time and funds for placing the land use information on cards for use by STORM.

2. Pollutographs. Assuming that the model has been calibrated on single land use basins, the application becomes a matter of inputting those factors which are a function of land use for each land use represented in each subbasin. A separate set of E-T cards are to be punched for each subbasin. The subbasins can be identified by number and river mile along the receiving stream where the subbasin is assumed to empty. The subbasin cards can be grouped in reaches and those reaches run in a single pass.

In studies where the effects of storm water runoff on the receiving waters are assessed, it has been conventional to study a "critical" period of in-stream water quality. The criteria for selection of this critical period are somewhat indefinite but include warm weather and low flow conditions. The effects of several historical storm water runoff events on the receiving water are usually studied. This procedure was followed in the St. Louis (Reference 12), Atlanta (Reference 13) and Oconee studies (Reference 13).

The STORM model is then used to predict the wet weather storm water runoff pollutographs for the events during the critical period. (It will normally be required to use about 5 years of precipitation data in STORM prior to the selected events so that the effects of initial conditions can be neglected.) The current version of STORM will print the hourly pollutograph for each selected event (maximum = 20) although it gives a one line summary of each event that occurred during the period of simulation. It will normally be convenient to modify the program slightly so as to punch the pollutographs directly on cards or place them on tape/disk. This allows the pollutographs to be used directly by the receiving water assessment model without any intermediate data manipulations by the user. A future version of STORM will contain a simple in-stream water quality assessment module, as well as a module to route and combine flows and quality from subbasins.

3. Storage-Treatment Rate Analysis. STORM has a great deal of potential for providing information which could assist in the preliminary sizing of storage volumes and treatment rates to achieve desired control of storm water runoff. If treatment of the stored water is not envisioned, the treatment rate could be equated to a pumping rate so that the model could be used to study a flood control reservoir with a constant release

rate. Minor modifications to the model would allow the release rate to be made a function of the head on the conduit since a variable release rate is more advantageous for optimum flood control operation. These options will be available in a future version.

If values for both storage and treatment are specified, the model will analyze the system's response to the continuous record of runoff hydrographs. The runoff amounts are computed by simulation of the rainfall-runoff process as discussed earlier. Part of the purpose for a continuous analysis involves the interaction of successive runoff events. From a flood control standpoint, it would be most advantageous to have the reservoir in an empty state at the beginning of each runoff event. This is often not possible from a practical standpoint and because of the random occurrences of storms. Obviously, if the reservoir is partly full from a prior storm, it will be less effective in capturing all of a subsequent runoff event.

STORM provides information on the characteristics of the stored runoff such as the time storage began, time of spill (or maximum storage), hours to empty, hours between use of storage, to name a few. Statistics are also presented on the utilization of storage. These include the average storage at each hour of each event, the average annual number of hours each hundredth of an inch of storage was utilized. These two statistics are used to compute a normalized storage utilization curve which depicts the percent of time that the water in storage was less than or equal to a given percentage of the maximum storage.

Figure 6 shows an example of the normalized storage utilization curve. It gives a quick visual measure of the relative efficiency of the

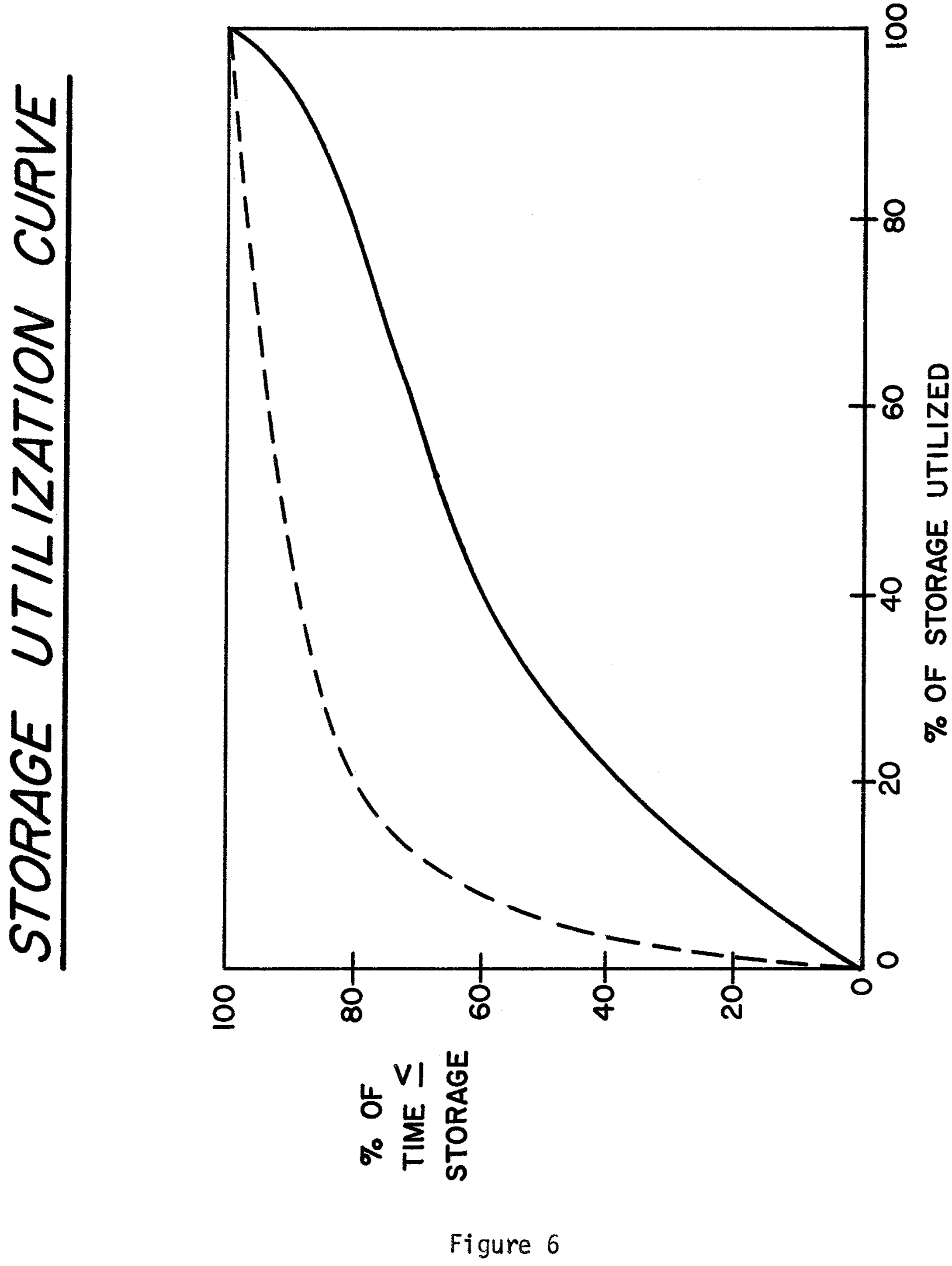

STORAGE UTILIZATION CURVE
% OF TIME ≤ STORAGE
% OF STORAGE UTILIZED
0
20
40
60
80
100
0
20
40
60
80
100

Figure 6

selected storage volume and treatment rate. It gives an estimate of the response of the storage/treatment combination to the continuous sequence of runoff hydrographs. Referring to Figure 6, one can see that the combination represented by the dashed line is not an efficient combination since, for example, 80% of the time only about 20% of the storage was utilized. Since the reservoir level would be in the lower 1/5 of the storage 80% of the time, we would conclude that either the treatment rate or the maximum storage capacity is too high. The decision to lower either the storage or the treatment rate must be made in terms of the economics of both and the criteria for overflows from storage. The solid line on Figure 6 shows a more efficient combination of storage and treatment rate.

The model is designed to compute statistics for a matrix of storages and treatment rates. Computational time is the only limiting factor on the number of combinations that should be analyzed in a given run. The computer run times are also proportional to the length of continuous record to be studied. Experience in HEC has shown that computational time is extremely sensitive to the combination of storage and treatment rate. In fact, the computer time is directly proportional to the storage volume and inversely proportional to the treatment rate. The reason for the sensitivity is that for the larger storages and smaller treatment rates, there is less spill and the program must keep account of more water for a longer period of time. The HEC has added an option in the model so that the user may select whether or not he will compute the ages of storage since these involve significant computer time for the high storage-low treatment rate combinations.

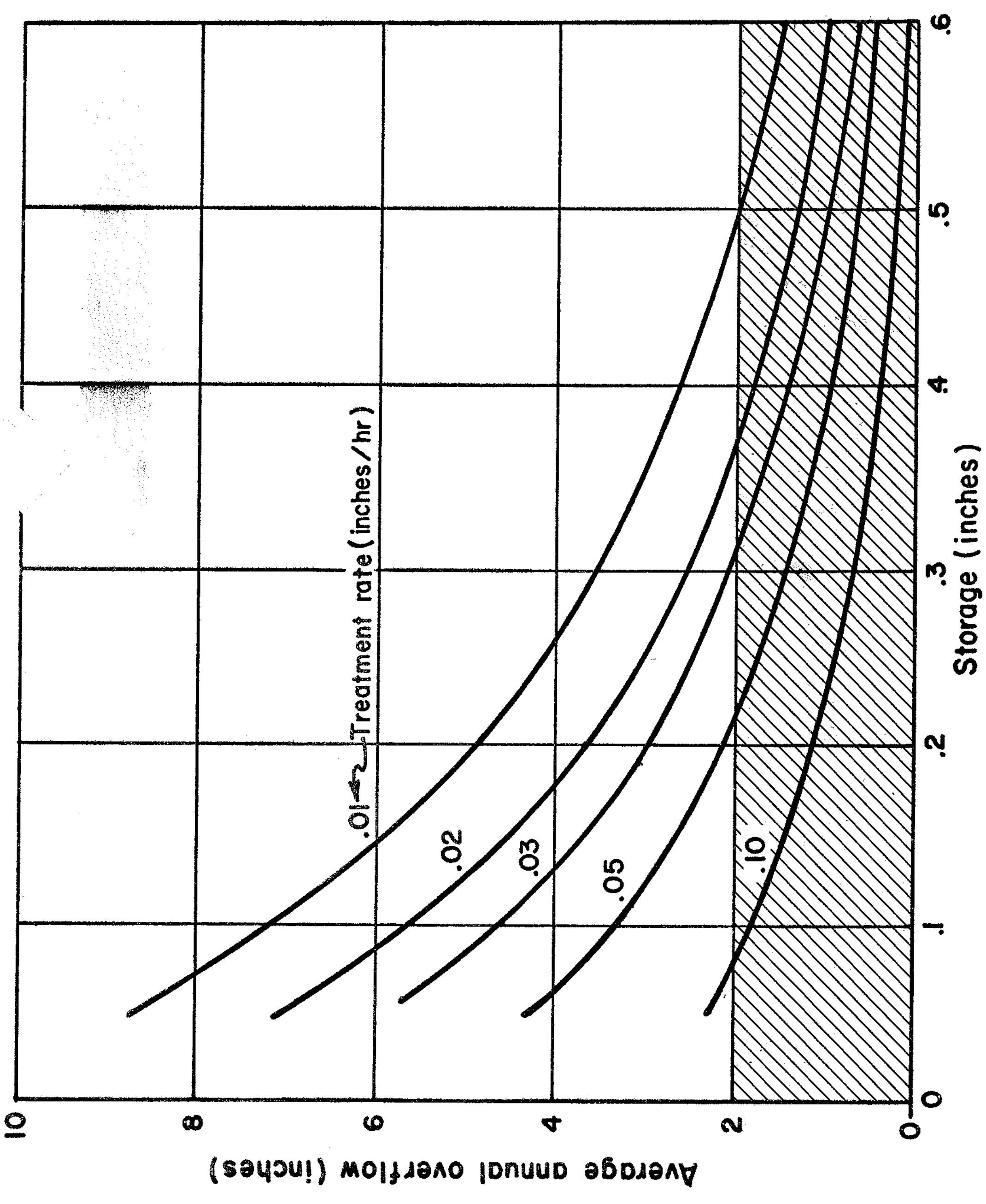
Figure 7 shows a set of quantity performance curves which were plotted from an analysis of a matrix of storage and treatment rate combinations. One can see that if a standard of not more than 2 inches overflow per year was adopted, the shaded region on Figure 7 represents the variety of storage and treatment rates that would satisfy the standard. Figure 8 shows an analagous set of curves for quality (BOD, in this case). The shaded region represents a variety of combinations of storages and treatment rates that would release not more than 5000 pounds of BOD per year in overflows from storage.

Another standard could be adopted where two or more criteria could be combined such that both must be met simultaneously. For example, the decision criteria could be:

(1) not more than 5 overflows per year, and

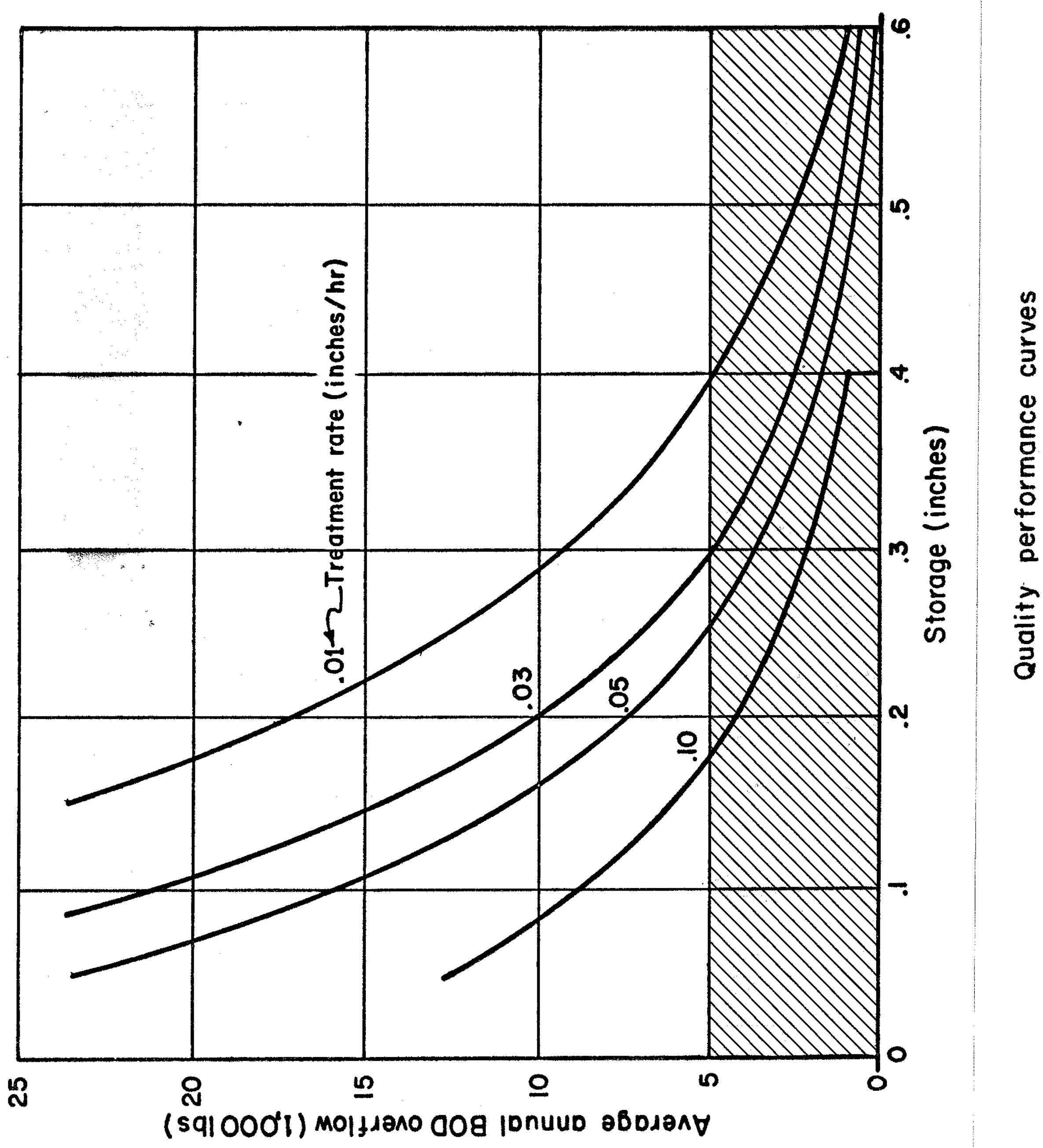
(2) not more than 2500 pounds of BOD overflow per year.

A family of curves relating storage, treatment rate and average annual number of overflows can be prepared from the output from STORM. These curves are displayed in Figure 9 where a region of less than or equal to 2500 pounds of BOD overflow per year has been shaded. It can be seen that point A represents the amount of storage and treatment rate which will exactly satisfy both criteria. Point A is located at a storage of 0.39 inches and a treatment rate of 0.033 inches per hour and represents minimum requirements for both storage volume and treatment rate. The entire region above the 5 overflow line and the 2500 pounds of BOD overflow line would more than satisfy both criteria. A solution is then pursued which would satisfy the criteria at minimum cost.



Quantity performance curves

Figure 7



Quality performance curves
Storage (inches)
Average annual BOD overflow (1,000 lbs)
Treatment rate (inches/hr)
.01
.03
.05
.10
0
.1
.2
.3
.4
.5
.6
0
5
10
15
20
25

Figure 8

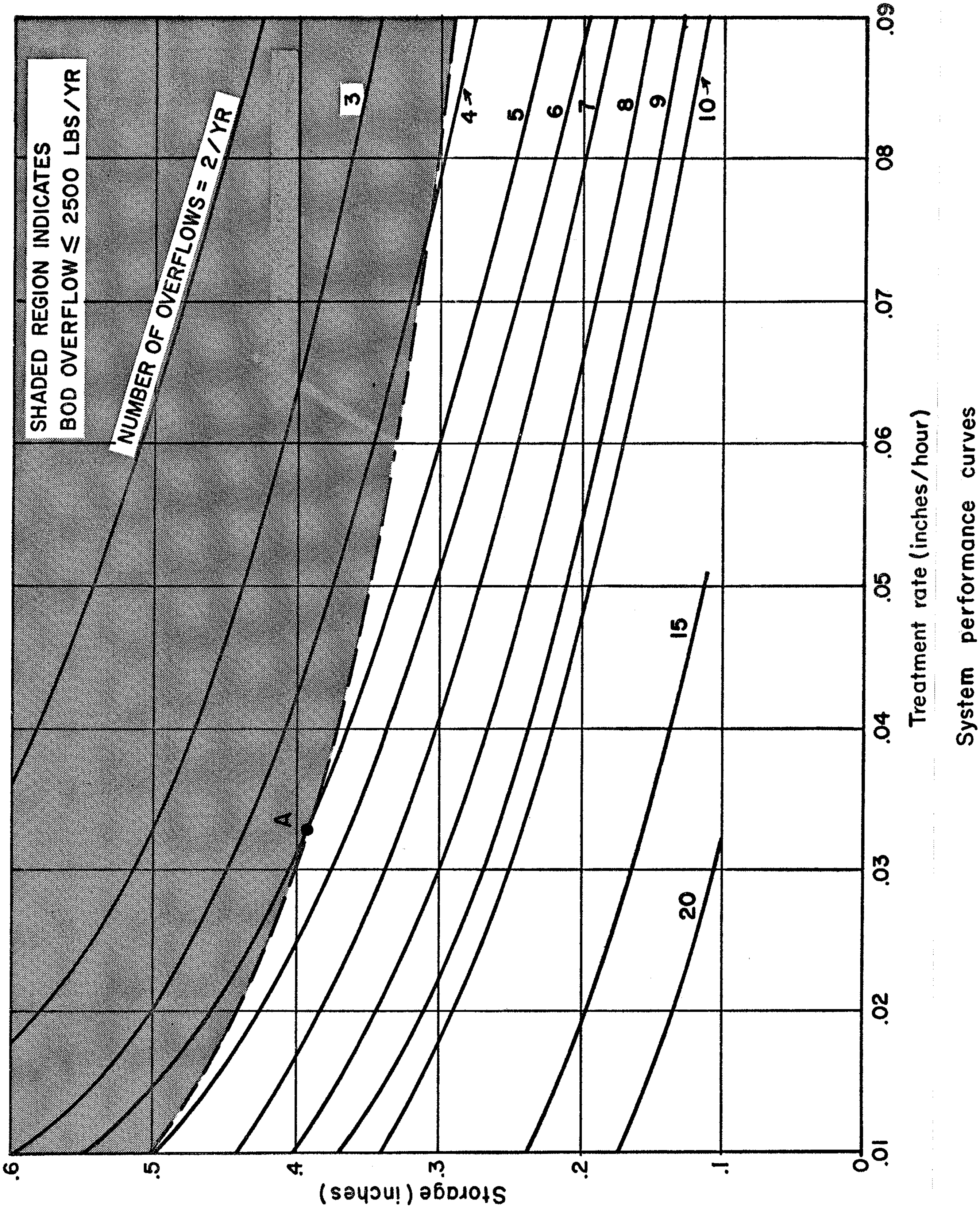

SHADED REGION INDICATES
BOD OVERFLOW ≤ 2500 LBS/YR
NUMBER OF OVERFLOWS = 2/YR
3
4
5
6
7
8
9
10
15
20
A
Storage (inches)
Treatment rate (inches/hour)
System performance curves
.6
.5
.4
.3
.2
.1
0
.01
.02
.03
.04
.05
.06
.07
.08
.09

Figure 9

Another use of the output from STORM is to analyze the percent removal of pollutants by virtue of detainment in the storage reservoir. The current version does not model the treatment process itself nor the settlement and decay of pollutants while in storage. Therefore, the analysis is based entirely on detainment of the runoff until the treatment plant can accommodate it. Figure 10 shows an example of the percent of BOD removed from runoff versus storage capacity. In this analysis it was assumed that the treatment plant removed 90 percent of all BOD in the influent and the BOD concentration in the overflow was the same as the influent. Therefore, the curve becomes assymtotic to 90 percent removal as storage is increased and all runoff can be treated. A future version of STORM will contain algorithms for treatment and settlement of pollutants in storage. This will allow a more realistic appraisal of the effect of storage and treatment on the quality and timing of runoff released to the receiving waters.

The preceding examples were only a few illustrations of how STORM can be used to study the quantity and quality of storm water runoff. Many other specialized criteria and methods can be utilized as required by the application.

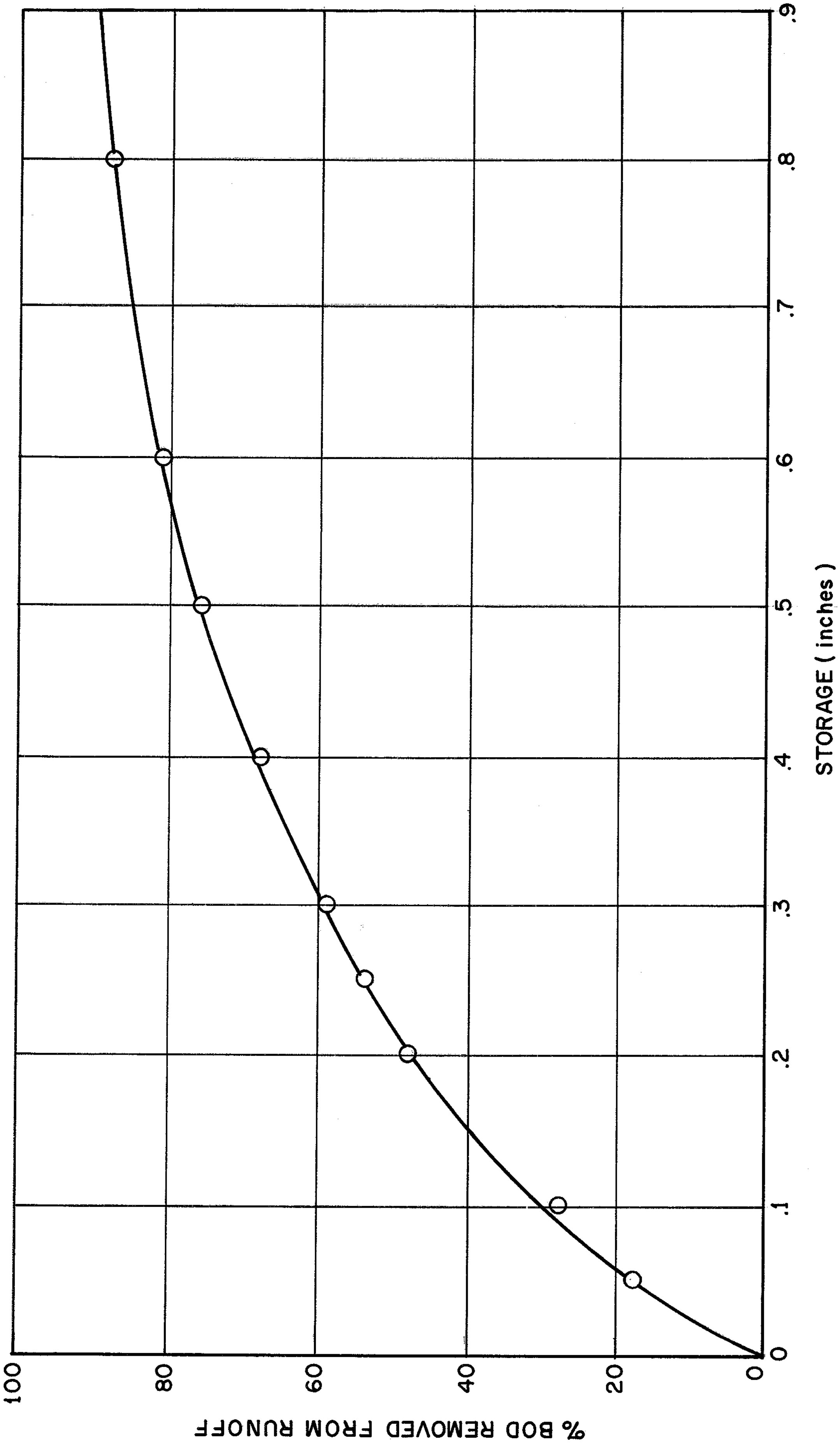

% BOD REMOVED FROM RUNOFF
STORAGE (inches)
0
20
40
60
80
100
.1
.2
.3
.4
.5
.6
.7
.8
.9

Figure 10

IX. ADDENDUM

DESCRIPTION OF SCS METHOD OF RUNOFF DETERMINATION AS PROGRAMMED IN STORM

Robert J. Cermak

September 1980

DESCRIPTION OF SCS METHOD OF RUNOFF
DETERMINATION AS PROGRAMMED IN STORM

Introduction

The purpose of this write-up is to provide documentation of the way STORM computes the quantity of runoff using what is referred to as the "SCS Method." The current STORM Users Manual (August 1977) does not describe this option of runoff determination in sufficient detail.

Acknowledgment: Portions of Art Pabst's STORM lecture notes, prepared for the 1978 Urban Hydrology training course, will be used to illustrate some definitions and concepts.

SCS Method

STORM contains a runoff procedure derived from the SCS Curve Number technique but modified to operate continuously at STORM's fixed 1-hour time interval. Curve numbers are not used in STORM; the SCS runoff equation is

$$Q = \frac{(P - IA)^2}{P - IA + S} \tag{1}$$

where

Q = accumulated runoff

P = accumulated precipitation

IA = initial abstraction

S = soil moisture capacity

This equation is graphed in Figure 1 for various values of S and assuming IA = 0.2S.

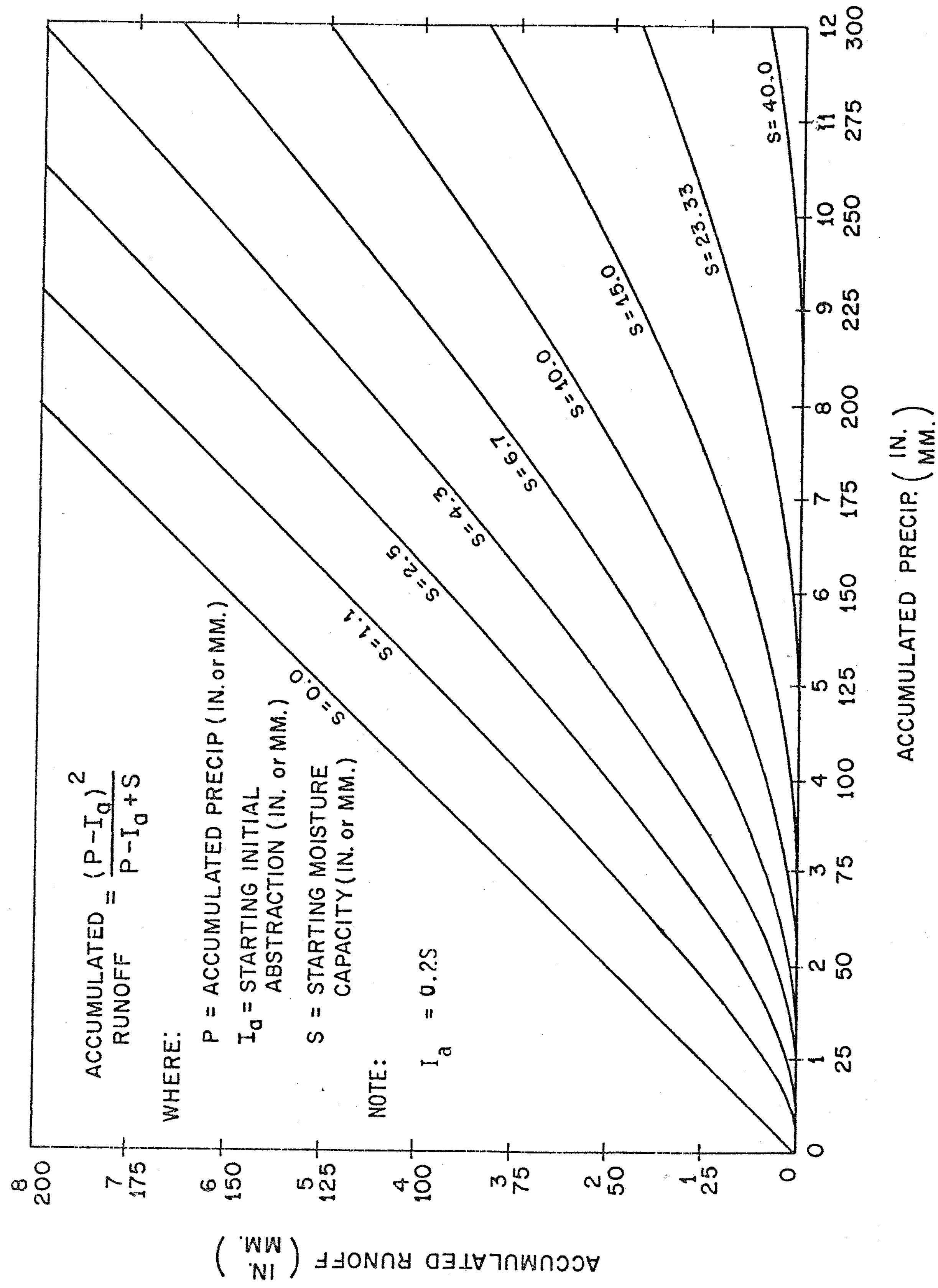


Figure 1. SCS RUNOFF PROCEDURE

IA represents all initial losses (interception, depression storage) that occur prior to the time when runoff begins. Figure 2 illustrates the conceptual storages, IA and S.

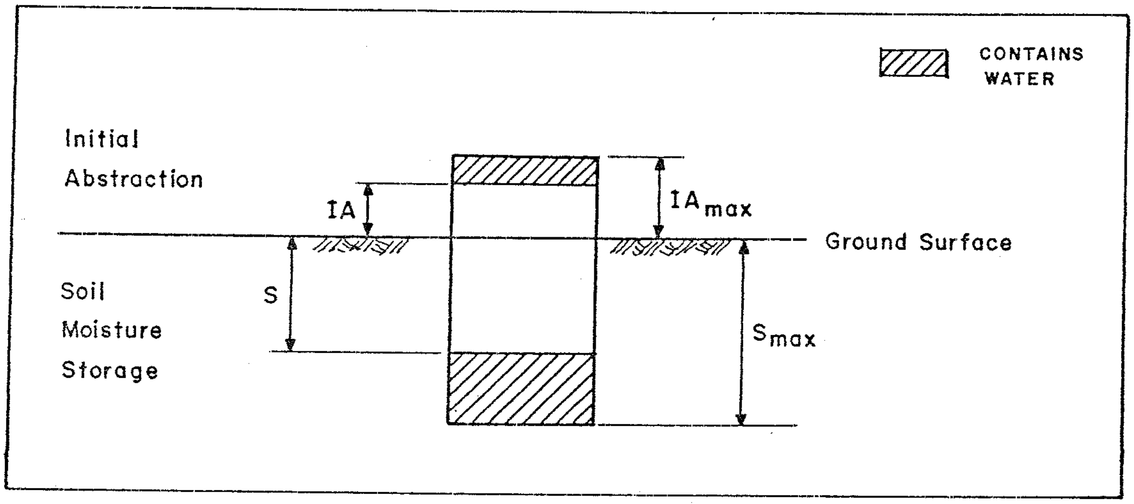


Figure 2

Conceptual Storages

The original SCS Curve Number technique was intended to compute <u>total</u> storm runoff volume. When the procedure was programmed in STORM the assumption was made that the SCS runoff equation could also be used to represent cumulative runoff during a storm event.

Input Parameters

The user must specify values for the following parameters.

Card-Field	Variable	Description
E5-2	DEPR	Maximum initial abstraction capacity (IA)
E5-3	ACTIA	Starting value of IA
E5-5	SMAX	Maximum soil moisture capacity (S)
E5-4	SACT	Starting value of S
E5-6	RATEIN	Maximum percolation rate
E5-7	PERCMX	Maximum deep percolation rate
E4-6	EPRC	Exponent in deep percolation equation
E4-5	EERC	Exponent in evapotranspiration equation

Runoff Calculation During a Storm Event

Once precipitation begins, the current values of IA and S (call them IA* and S*) are fixed and used in equation (1) throughout the storm event to compute cumulative runoff. For example, the cumulative runoff at the end of the previous hour would be

$$Q_{t-1} = \frac{(P_{t-1} - IA^*)^2}{P_{t-1} - IA^* + S^*}$$

and at the end of the current hour

$$Q_t = \frac{(P_t - IA^*)^2}{P_t - IA^* + S^*}$$

The incremental runoff for the current hour, ΔQ_t, would then be computed as

$$\Delta Q_t = Q_t - Q_{t-1}$$

Meanwhile a separate accounting of the actual changing values of IA and S continues to take place (as described in the next section) but is not used in the current storm. When precipitation stops, the updated IA and S become starting conditions for the recovery functions which operate during dry periods.

Moisture Accounting During a Storm Event

Let ΔP_t be the amount of precipitation (rainfall or snowmelt) occurring in hour t and ΔQ_t be the amount of runoff for the same time interval. (ΔQ_t would be computed as described in the previous section.) During a storm the following moisture accounting takes place:

- IA is decreased by ΔP_t, $0 \leq IA \leq IA_{max}$
- S is decreased by $\left[\Delta P_t - \Delta Q_t - IA^*\right]$, and

  increased by $\left[PERCMX \left(\frac{S_{max} - S_{t-1}}{S_{max}}\right)^{EPRC}\right]$, $0 \leq S \leq S_{max}$

Available initial abstraction storage (IA) is decreased by the amount of precipitation until there is no IA storage left. Soil moisture capacity (S) is decreased by infiltration; i.e., the difference between precipitation and the sum of runoff (ΔQ_t) plus initial abstraction storage at the start of the storm (IA*). Simultaneously, S is being increased by deep percolation at the maximum rate (PERCMX) adjusted by a ratio $((S_{max} - S_{t-1})/S_{max})$ that reflects current status (wet or dry) of soil moisture. An exponent (EPRC) is available to reflect nonlinearity in the deep percolation equation.

Figure 3 illustrates the change in IA and S during a storm. Figure 4 shows the variation in deep percolation adjustment ratio with selected integer exponents (EPRC).

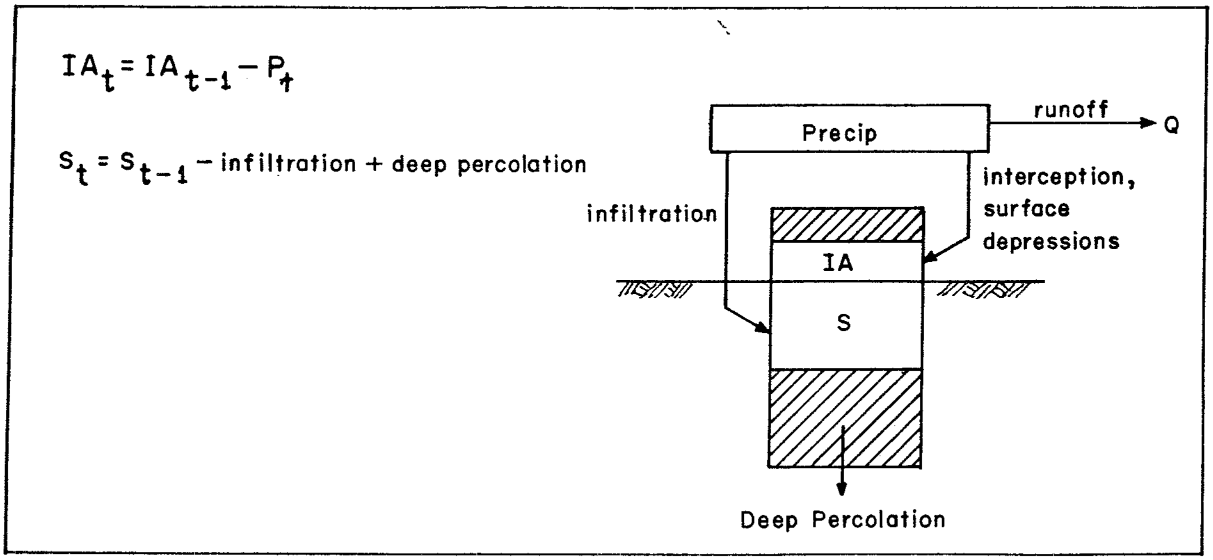


Figure 3

Moisture Accounting During Precipitation

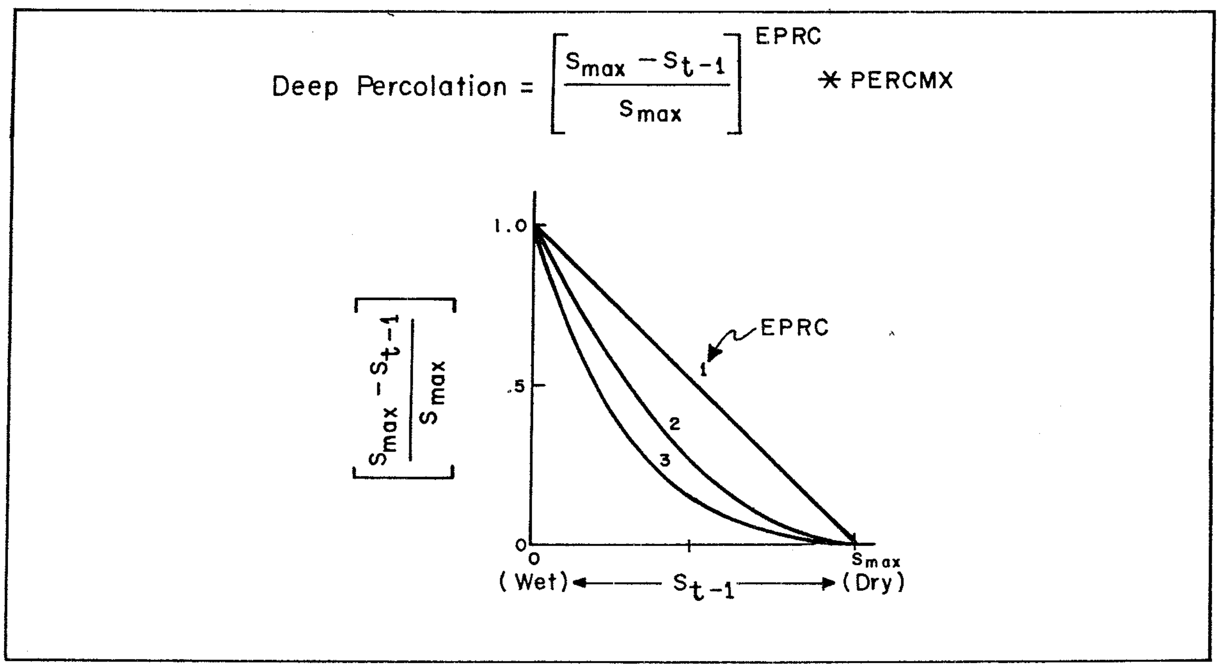


Figure 4

Deep Percolation Equation

Soil Moisture Accounting During Dry Periods

Initial abstraction storage recovers during dry periods through evapotranspiration to the atmosphere and percolation to the soil moisture zone. Evapotranspiration is removed at the potential rate (PET). Average daily values of pan evaporation (provided by the user as input) are considered equivalent to PET. Percolation of water from IA to S occurs at the maximum rate (RATEIN) modified by the relative amount of moisture present in the soil. The percolation equation is graphed in Figure 5.

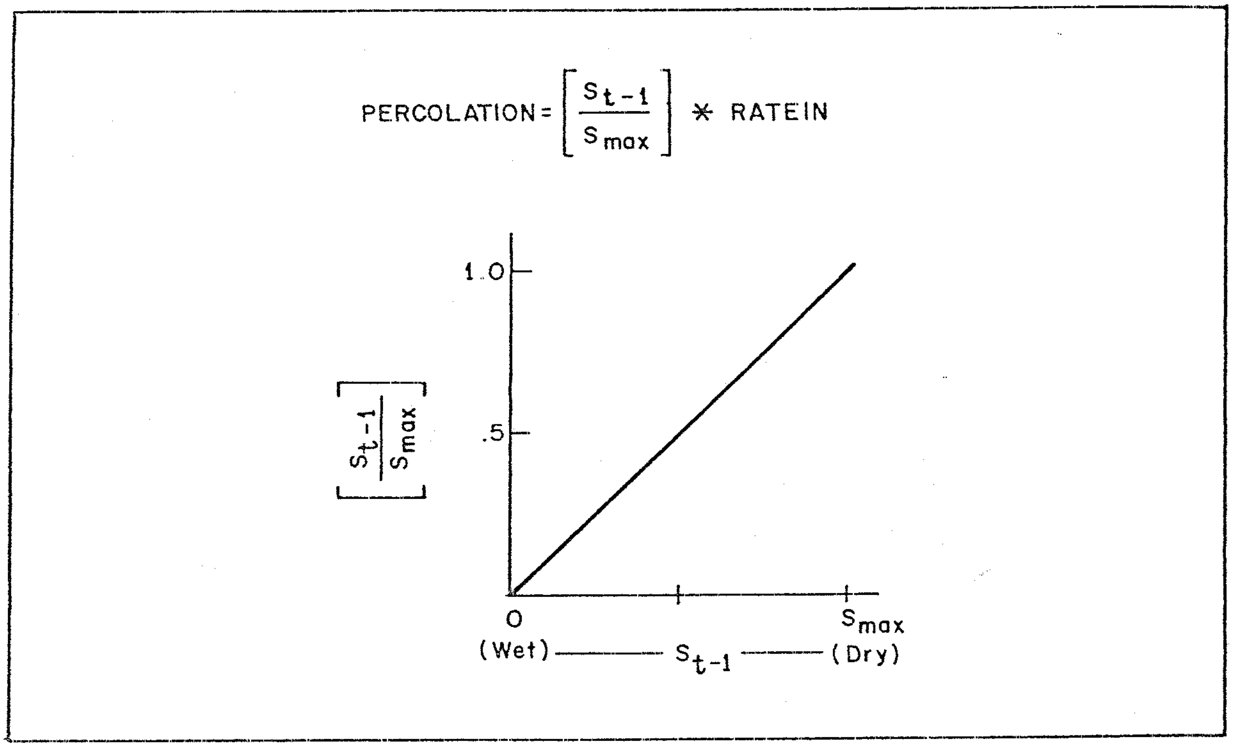


Figure 5

Percolation Equation

Change in soil moisture capacity (S) during dry periods is the result of (1) percolation from IA, (2) deep percolation, and (3) evapotranspiration. Percolation, as described above, adds water to soil moisture storage and thus decreases S. The deep percolation function is the same as was previously described for the water balance during a storm event. The evapotranspiration (ET) function is similar to the deep percolation function; both contain the relative soil moisture ratio raised to an exponent (Figure 4), but the ET formula has an additional constant term (0.7).

$$ET = (0.7) * \left[\left(\frac{S_{max} - S_{t-1}}{S_{max}} \right)^{EERC} \right] * PET$$

Soil moisture accounting for IA and S during dry periods is illustrated in Figure 6.

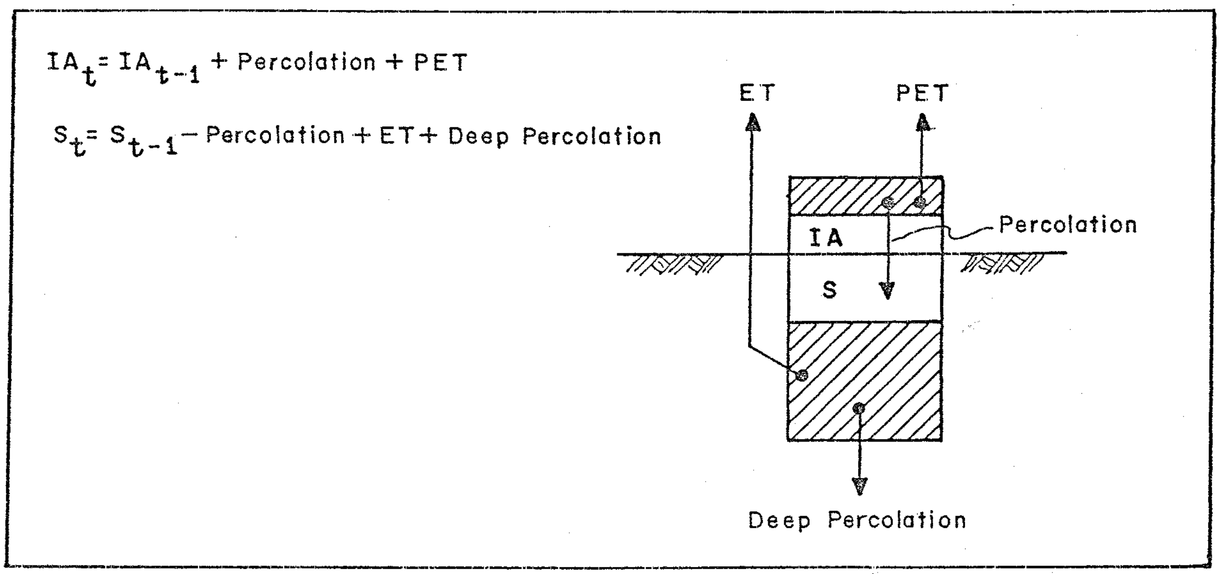
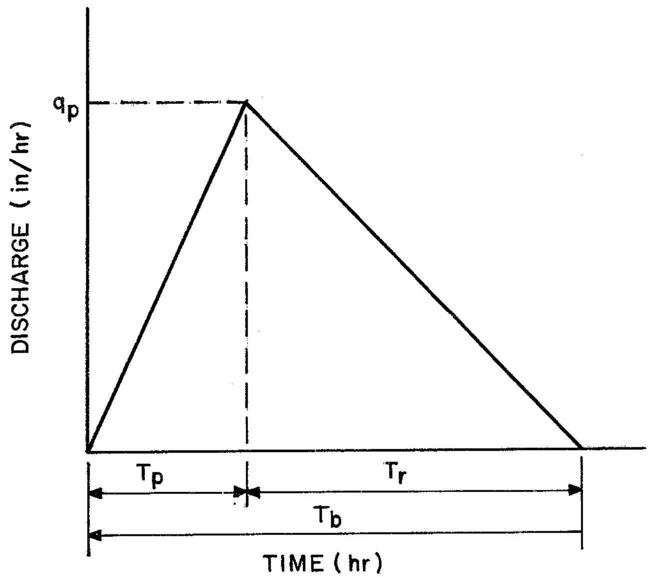


Figure 6

Moisture Accounting During Dry Periods

SCS Triangular Unit Hydrograph

Runoff transformation (from rainfall excess to subbasin runoff hydrograph) can be modeled by STORM using the SCS triangular unit hydrograph.



q_p = peak flow

T_p = time to peak

T_r = time of recession

T_b = time of base = T_p+T_r

Q = total volume

Peak Flow Rate Equation

$$Q = \frac{q_p T_p}{2} + \frac{q_p T_r}{2} = \frac{q_p}{2}(T_p+T_r)$$

$$q_p = \frac{2Q}{T_p+T_r} = \frac{2Q}{T_p(1 + T_r/T_p)}$$

$$\text{let } K = \frac{2}{(1 + T_r/T_p)}, \quad \text{then } q_p = \frac{KQ}{T_p} \qquad \left\{ \begin{array}{l} q_p \text{ (in/hr)} \\ Q \text{ (in)} \\ T_p \text{ (hr)} \end{array} \right.$$

$$\text{or} \quad q_p = 1.00833 \frac{KAQ}{T_p} \qquad \left\{ \begin{array}{l} q_p \text{ (cfs)} \\ A \text{ (acres)} \end{array} \right.$$

Unit Hydrograph Parameters

Ratio of time of recession to time to peak (T_r/T_p) and subbasin time of concentration (T_c) are the two unit hydrograph parameters that must be provided by the user to STORM.

Time of concentration (T_c) is defined as the time it takes runoff to travel from the hydraulically most distant part of the watershed to the point of reference. Lag (L) is the time from the center of mass of rainfall excess to the peak rate of runoff. T_c and L are related by an empirical equation.

$$L = 0.6\ T_c$$

Time to peak (T_p) and lag (L) are related by their respective definitions.

$$T_p = 1/2\ \Delta t + L$$

where Δt = time interval of unit excess rainfall (always 1 hour in STORM).

Substituting, this expression becomes

$$T_p = 0.5 + 0.6\ T_c$$

By specifying T_c (which defines T_p) and the ratio T_r/T_p (which determines K), and knowing the subbasin area (A) and unit hydrograph volume (Q = 1 inch), the peak discharge and shape of the unit hydrograph is set.

Although the parameters define a triangular unit hydrograph, STORM, working with a fixed 1-hour time period, computes the <u>volume</u> under the unit hydrograph in each time interval and does not deal with the actual ordinates of the unit graph. The sequence of 1 hour unit hydrograph volumes is then applied to the rainfall excess to determine the runoff <u>volume</u> hydrograph. An example is given below to demonstrate the unit hydrograph computations.

<u>Example</u>

Input to STORM: $T_c = 20$ min (0.33 hrs)

$T_r/T_p = 2.43$

$$T_p = 0.5 + 0.6\ T_c = 0.70 \text{ hrs}$$

$$T_r = (2.43)(0.70) = 1.68 \text{ hrs}$$

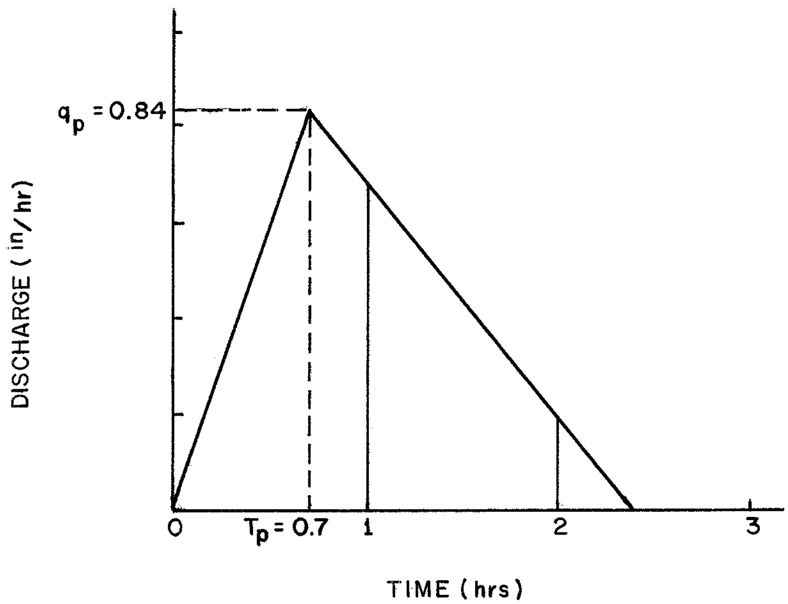
$$T_b = T_p + T_r = 2.38 \text{ hrs}$$

$$q_p = \frac{KQ}{T_p} \qquad K = \frac{2}{1 + T_r/T_p)} = 0.59$$

$$Q = 1 \text{ in}$$

$$q_p = \frac{(0.59)(1)}{(0.70)} = 0.84 \text{ in/hr}$$

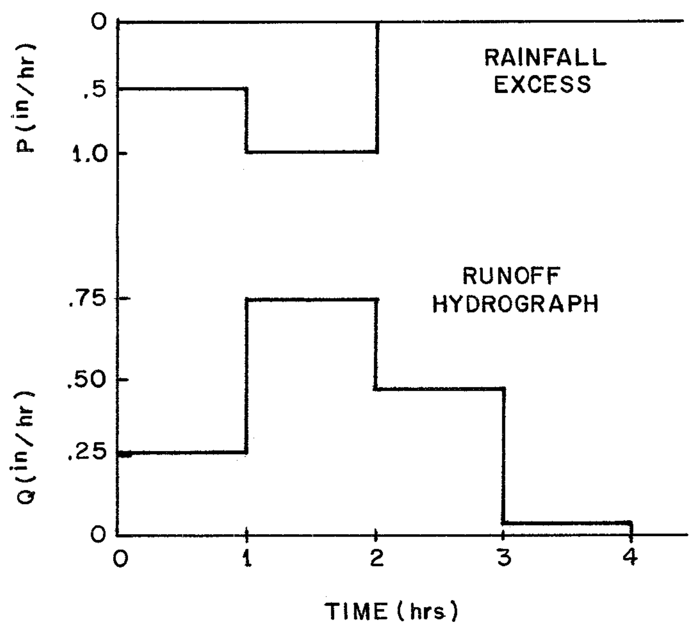
Unit Hydrograph



Volume Under Unit Graph

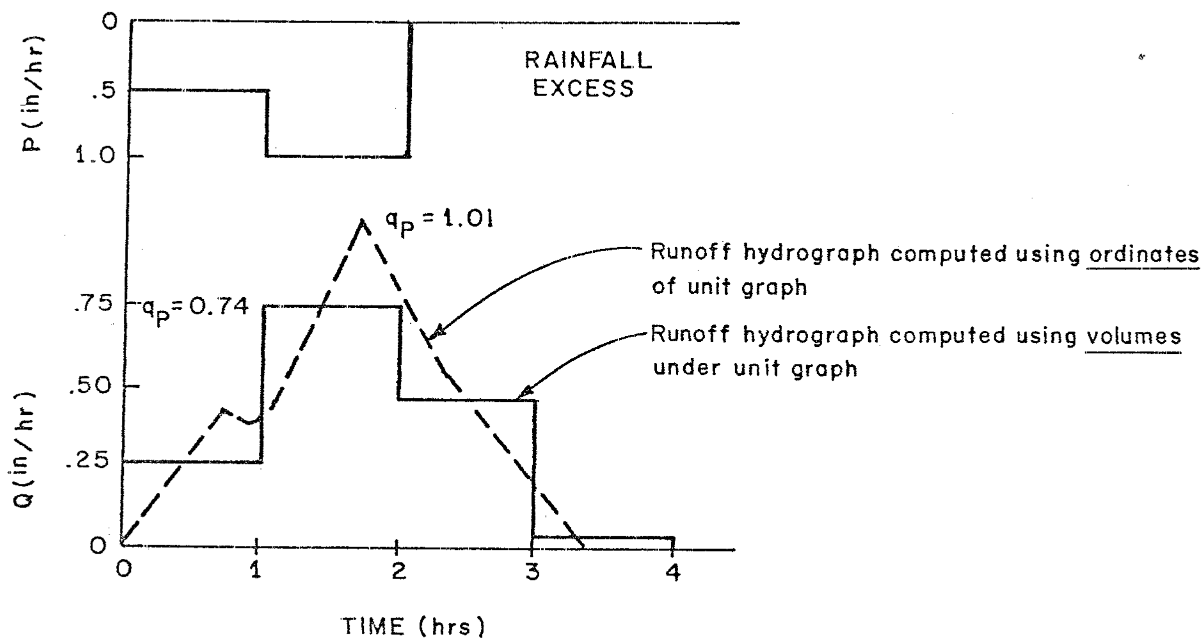
Hour	Volume
1	0.52
2	0.44
3	0.'44
	1.00 inches

Computed Runoff Hydrograph



Hr.	Runoff Volume	
1	(.5)(.52)	= .26
2	(.5)(.44)+(1.0)(.52)	= .74
3	(.5)(.04)+(1.0)(.44)	= .46
4	(1.0)(.04)	= .04
		1.50 in

If instead of using volumes under the unit hydrograph in 1-hour intervals, STORM were able to compute (<u>which it cannot</u>) ordinates of the unit graph and apply them to the excess rainfall, the runoff hydrograph would be as shown below.



The difference in peaks between the ordinate derived and volume derived runoff hydrographs, 1.01 in/hr vs. 0.74 in/hr, demonstrates the reduction in peak discharge that can be expected from the way STORM applies the SCS triangular unit hydrograph.

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